12th von Karman Lecture

Planetary Exploration: Earth's New Horizon

H. M. Schurmeier
CalTech Jet Propulsion Laboratory, Pasadena, Calif.

I. Introduction

I HAVE always been sorry that my undergraduate and graduate days at Caltech were such that I did not get to know Theodore von Karman. In the many years since then, the desire to have known this extraordinary man increased each time I encountered a new area where he had left his mark. Although von Karman's technical contributions in rocketry and other aspects of astronautics form many of the foundations on which present day planetary exploration is based, his best-known role has been institutional. He helped to create the aeronautical R&D establishment, personally assisted the founding of some of the key institutions, and trained a portion of the important technical population carrying out the exploration of the solar system. But I think he played a more important philosophical role. As a practicioner of a special kind of applied research, he helped pioneer the interaction of science and technology under Government sponsorship, a collaboration which led to and made possible the exploration of the planets.

In this lecture I propose to examine planetary exploration in terms of the interaction of technological growth with scientific progress and the intangibles associated with exploring the unknown. I shall limit my field to the unmanned exploration of the planets (and satellites, except our own) of the solar system. I shall attempt a descriptive model of the endeavor, recount its activities and the achievements of the past decade or so, characterize the current state-of-the-art, and look at some of the planetary mission opportunities for the next decade. Finally, I shall put the case for the ongoing exploration of the planets as a worthwhile endeavor for our civilization, based on the significant developmental achievements of the past, the mature capability of the present, the challenging opportunities visible in the near future, as a source of new understanding of our world (in the largest sense), and an expression of the vigor of our culture.

Our planetary space flight effort has been and is a highly successful and rewarding effort for the nation, as a demonstration of our technical capability. It is a contribution to humanity's scientific knowledge whose practical value is

H. M. Schurmeier

Harris M. Schurmeier is Deputy Assistant Laboratory Director for Flight Projects and Project Manager for the Mariner Jupiter/Saturn 1977 Mission at the Caltech Jet Propulsion Laboratory.

He was born in St. Paul, Minnesota, July 4, 1924. He was graduated from New Trier High School, Winnetka, Illinois, and served as a Naval Aviator at the end of World War II. The California Institute of Technology awarded him a Bachelor of Science degree in Mechanical Engineering in 1945, a Master of Science degree in Aeronautical Engineering in 1948, and a Professional Degree in Aeronautical Engineering in 1949.

Upon joining the Jet Propulsion Laboratory in 1949, Mr. Schurmeier served as Wind Tunnel Section Chief and Aerodynamics Division Chief. For a brief period, he served as Deputy Program Director of the Sergeant Project, the U.S. Army's ballistic guided missile, eventually leaving this post to organize and head the Systems Division. Mr. Schurmeier was Ranger Project Manager from December 1962, until completion of the lunar photo-reconnaissance missions in 1965. He was the Manager of the Mariner Mars 1969 Project and was appointed to his current position in Sept. 1969.

Mr. Schurmeier has served as Chairman of the Supersonic Tunnel Association (1955-56), a member of the NASA Research Steering Committee on Manned Space Flight (1959), and a member of the NASA Research Advisory Committee on Missile and Space Vehicle Aerodynamics (1961-62).

The NASA's Medal for Exceptional Scientific Achievement was presented by President Lyndon B. Johnson to Mr. Schurmeier in March 1965, following the successful Ranger IX lunar photographic mission. Mr. Schurmeier also received the 1965 Astronautics Engineer Award at the annual Dr. Robert H. Goddard Memorial Dinner in Washington, D.C., and earlier received the NASA Public Service Award. In 1969 he received the NASA Exceptional Service Medal following the successful Mariner Mars 1969 mission.

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beginning to be realized, and a widening of our horizons beyond this small planet. So far, in the 1960's and 1970's, more than 40 spacecraft have been launched from Earth in apparent planetary attempts. In the past decade, successful unmanned missions have returned important information from Mars, Venus, Mercury, and Jupiter. Now we are preparing to land instruments on Mars and are progressing with efforts to send probes into the atmosphere of Venus and comprehensive instrument packages past Jupiter and Saturn. We have the technical capability to remotely fly by, orbit, enter dense atmospheres, or soft-land on surfaces under any but extreme conditions, to telemeter scientific data to Earth from the far reaches of the solar system, and to design intrumentation and spacecraft to obtain almost any information desired.

In view of the human urge to explore, the scientific importance of the planets, the mature state-of-the-art, and the demonstrated technical and cost performance, we should now move ahead toward the return on our investment through the mission opportunities of the next decade.

I would like to describe the dynamics of planetary exploration for a moment in terms of four imperatives which equally condition any exploration. They are: scientific interest and objectives, technical capability, the natural environment, and economics. There is an additional dynamic imperative, political causes and effects, which though extremely powerful at the outset of the space and planetary exploration program are less influential today.

In this quadripartite model, though the money is spent largely here on Earth for technology which is in turn employed in space to withstand environmental effects (including those of sheer distance and duration), the payoff is largely (and ostensibly) in terms of scientific knowledge, performing experiments, and fulfilling scientific objectives. Only in the best of times, and then not easily, can pure science compete successfully for national attention in the economic sense. Thus planetary exploration has inevitably been insignificant on a national scale, low on the agenda, small in the budget. It might not have begun in our time, except that the USSR and the U.S. seized upon space exploration as a medium of peaceful competition for national prestige, an activity in which all participants have made gains, but in which global science is the ultimate beneficiary. The planets offer no opportunity for near-term industrial exploitation, and are not subject to political annexation, though flags and other national symbols have flown there. Though politics may have given the thrust which started and continued to drive planetary exploration, this activity is not a political effort in the long term.

It is rather the dynamic balance between scientific objectives and economic restraint here on Earth, and between technical capability and the uncertainties of the physical universe (which I call environment) that drives and shapes our planetary exploration. The first pair tends to shape and pace the program, the second to define the actual performance. Naturally, success or failure can be a stimulus affecting both scientific interest and the budget, while scientific interest and/or a changed level of effort can change and improve the technology. But as first-order effects, these two balances of the four factors determine the fate of planetary exploration.

A case of economics might be the relative launch rates of the U.S. and Soviet programs. The U.S. has obviously been willing to spend less for launch vehicles, preferring, as we shall see, higher reliability per mission (at an assumed lower total cost). An effect of scientific interest and objectives, overcoming one aspect of economic restraint, is the broadening of U.S. exploration to Mercury and Jupiter in the past few years. An effect of technological advance is the Mercury mission via Venus, and Saturn via Jupiter, using the gravity-assist technique. Another and more vivid effect is the rise in U.S. interplanetary telemetry rates from 8 bits/sec at Mars in 1964 to 117,000 bits/sec at Mercury last year. Environmental effects include setbacks to planetary landing plans when the low density of Mars' atmosphere and the high pressure and temperature of Venus' atmosphere were established by two successive Mariner missions.

Currently, I estimate that of the four balanced imperatives, three are generally favorable to planetary exploration: 1) The economic support is undeniably uncertain, but scientific interest is strong, stimulated by the results of early and recent planetary missions. 2) The technology is strong and vigorous, and seems to have the problems of exploring the solar system within its reach. 3) We have a better understanding of nature and the environmental problems we face in planetary exploration than ever before. Thus at this state of the balance, our prospects are good. Now let us see how we reached this point.

II. The Earthbound Exploration

A significant portion of present and near-term planetary exploration has been, is, and will be carried out through instruments located on the Earth, and these observations continue and improve a tradition which goes back decades and centuries before the first space flight. This work was called planetary astronomy until it became incorporated restrospectively with the space-based efforts and began to involve scientists of every discipline. But in another retrospective shift we must incorporate the preceding centuries of observation of the positions and motions of the known planets, whether performed in the service of ancient astrology or of Renaissance cosmology, into planetary exploration.

The field of study we call celestial mechanics is in fact the oldest science. The first instruments were simple but accurate angle-measuring devices without optics. These pretelescope instruments and the resulting measurements eventually reached a high degree of precision: a few sixteenth-century measurements of Mars permitted Johannes Kepler to work out his laws of planetary motion, which ultimately led to Newton's gravitational theory. Adoption of these theoretical models, and progressively better measurements using new techniques and instruments, permitted scientists to fairly accurately define planetary motions. More important, evolving gravitational theory permitted the calculation of the planets' masses, and made possible the discovery of at least one previously unknown planet, Neptune, from the perturbation of Uranus' orbit. These mass values, in turn, could be combined with telescopically measured or estimated sizes for the bodies to calculate the bulk densities of the planets. These data supported the first speculations about the compositional differences of other worlds.

Planetary exploration proper began with Galileo. The search for and discovery of new planets and their satellites (Table 1) derived from the invention of the telescope. Thousands of asteroids and dozens of planetary satellites have been added to the lists, some very recently (evidence of a thirteenth satellite of Jupiter is being reviewed at this writing). The telescopic observer and his photographic plate discover these objects, but it is the orbit calculation and confirming observation which certify them. The inventions of photography, which records the images for measurement and checking, and of the computer, which performs the calculations quickly and accurately, have each in turn revolutionized this science.

Now let us consider the telescope's primary role in planetary exploration: looking at the planet. This is what fascinated Galileo and nearly all who came after him. The fascination persists with spacecraft pictures from the first dim images of the lunar farside or of Mars to the latest high-resolution mosaics of Mercury or the spectacular color reconstructions of Jupiter. The important point about any planetary image is that in addition to its beauty it is a rich data package. Inferences follow quickly from such data, greatly stimulating scientific thought.

There was a great burst of interest in observational planetary astronomy in the latter part of last century, based mostly on the availability of good refracting telescopes; but for a number of related reasons the effort died away. A principal cause was the rampant speculation about life on Mars,

Table 1 Planets and satellites with discovery dates

Planet	Satellite	Discovery
Mercury	....	Antiquity
Venus	...	Antiquity
Mars	...	Antiquity
	Phobos	1877
	Deimos	1877
Jupiter	...	Antiquity
	V Amalthea	1892
	I Io	1610
	II Europa	1610
	III Ganymede	1610
	IV Callisto	1610
	XIII	1974
	IV Hestia	1904
	VII Hera	1905
	X Demeter	1938
	XII Adrastea	1951
	IX Pan	1938
	VIII Poseidon	1908
	IX Hades	1914
Saturn	...	Antiquity
	Rings	1655
	Janus	1966
	Mimas	1789
	Enceladus	1789
	Tethys	1684
	Dione	1684
	Rhea	1672
	Titan	1655
	Hyperion	1848
	Iapetus	1671
	Phoebe	1898
Uranus	...	1781
	Miranda	1948
	Ariel	1851
	Umbriel	1851
	Titania	1787
	Oberon	1787
Neptune	...	1846
	Triton	1846
	Nereid	1948
Pluto	...	1930

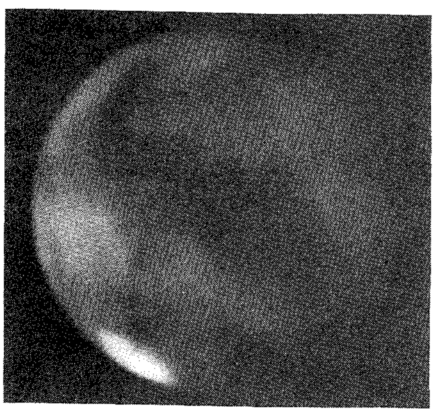

Fig. 1 Composite photograph made by superimposition of many images obtained in 1956 by R. B. Leighton at Mt. Wilson. North at top right; Trivium Charontis near limb, upper right.

based on interpretations of elusive detail which could not be objectively recorded. The combination of atmospheric turbulence with the limit of optical resolution and photographic sensitivity left too many critical questions open. As better telescopes, especially the large reflectors, came to be built, their astronomical range and the growing demands of stellar astronomy, together with the unfortunate imaginative reputation which planetary observation had acquired, turned away from the nearby solar system.

The problems of acquiring and recording a clear planetary image continued to be attacked, however. One such complex approach was made by R. Leighton, of Caltech, who developed an image-motion compensator, shot motion pictures and other multiple images of Mars and Jupiter, and made superimposed composite images in the 1950's (Fig. 1). The space program has brought new image-processing techniques to the service of the Earth-based observer, and has stimulated new waves of telescopic planetary observation, often in direct conjunction with planetary spacecraft missions. The spectroscope was applied to telescopes for solar and stellar astronomy over a century ago, and to the less bright planetary targets shortly after. With the advent of dry-plate photography, the instrument became the spectrograph, capable of direct recording over the long exposure times required. Many planetary spectrograms were obtained at the Lowell Observatory in the first decade of this century, while the ammonia and methane of the giant planets and the CO of Venus were positively identified at Mount Wilson in the early 1930's.[1]

The technology explosion of World War II brought many new tools to various fields of astronomy. One of these was the lead sulfide infrared detector, which G. P. Kuiper used with a spectrometer to detect the CO_2 of Mars (at 2 μ) and to survey all the planets in the infrared bands. He also detected the methane atmosphere of Titan in visible-light spectral bands.

Workers in this field ran a race with the space program for a key planetary datum. In 1963 Kaplan, Munch, and Spinrad were searching for spectral evidence of water on Mars; they found a strong CO_2 band in the near IR. From this they were able to define the pressure—abundance product. Comparing this to an older infrared CO_2 band, they were able to calculate an atmospheric pressure value (of 25 ± 15 millibars) which contrasted with most estimates and approximately anticipated the value which the Mariner 4 spacecraft mission would measure.[2] This quantitative technique enlarged the role of Earth-based spectroscopy in planetary exploration. Additional technical refinements to this art have taken the form of image intensification and improvement using image tubes and other electronic instrumentation.

Photometry began with rough naked-eye classification into stellar "magnitudes." A variety of instrument techniques made slow progress toward accurate measurement, especially difficult at the low light levels of many planetary targets, until the revolution in photometric research came after World War II when the photomultiplier tube became available. This sensitive device with its linear electrical output made photometry a most useful science in planetary research. Photometry is coupled with narrow-band filters to become a form of spectrometry with low-to-moderate spectral resolution but giving precise intensity values. In such fashion it was possible to determine that the "green" markings on Mars were contrast illusions. Photometry determined the rotation period of Pluto, a technique also applied to satellites and to dozens of asteroids. Photometric measurements of Mercury's surface anticipated at the microscopic level the recent spacecraft determination that the planet's surface is lunear in character. Photometric and other Earth-based studies of Mercury are surveyed by Morrison in Ref. 3. In 1974, photometric observation of a lunar dark-side occultation of Titan corrected that satellite's diameter estimate from 4850 to 5800 km.[4]

Radiometry, the broad-band extension of photometry to very long wavelengths used bulk-heating detectors, from fluid thermometers to the thermocouple, until the application of various quantum detectors in the early 1960's. Its contribution to planetary research has been low-to-moderate-resolution thermal mapping and the study of planetary thermal characteristics, including Jupiter's anomalous energy balance. A very-long-wave extrapolation of radiometry is radio astronomy. This science was boosted by advances in

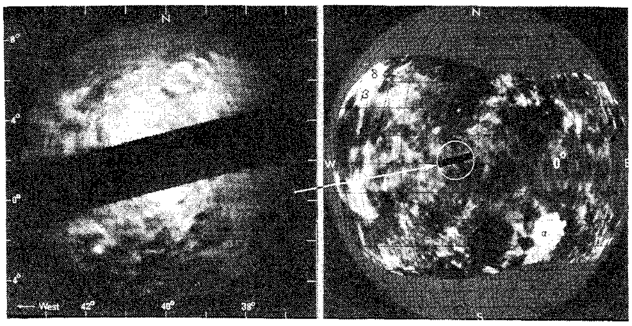

Fig. 2 Radar mapping and imaging of the surface of Venus, constructed by computer processing of range and Doppler data. The enlarged image at left was obtained in 1972/73.

communications and radar technology. Jupiter's decametric radiation was discovered in 1954, and radio observations led eventually to estimates of the Jovian magnetosphere, and, beginning with Venus, to temperature measurements on various planets.

The newest Earth-based technique of planetary exploration, and one of the most dynamic, is radar astronomy. The moon was detected by radar shortly after World War II. By 1960, the planet Venus had been detected by radar astronomers at MIT and Caltech and range measurements were obtained to refine the value of the astronomical unit. The 1962 conjunction of Venus found Soviet and American observers taking Doppler data to measure the slow retrograde rotation rate for the first time (previously, it had been guessed at over a wide range of values, with synchronous rotation getting the majority vote). In 1965, Dyce and Pettengill[5] found by radar measurement that Mercury's rotation was not locked to the sun, overturning a well-established conclusion. Meanwhile, Goldstein of JPL had identified surface features on Venus, regions of radar-frequency roughness, which he could track in their rotation. This began a remarkable process of radar mapping which, by combining range over the planet's curvature, Doppler as it rotates and moves relative to the Earth, and polarization and reflection intensities, through a computer program, defined recognizable crater-like features through an opaque atmosphere and at least 40 million km of space (Fig. 2). Similar "images" of the planets Mercury and Mars have also been obtained. The rings of Saturn have been detected by radar, and estimates of particle size have resulted; radar has also detected asteroids and planetary satellites. These data have been or will be correlated with spacecraft image data. However radar retains an unchallenged role in probing surfaces hidden by such atmospheres as that of Venus.

In this brief introduction to Earth-based planetary exploration I have deliberately taken an instrumental perspective, not so much because I am an engineer but because that is how the science and the community are characterized and categorized. I have tried to indicate the way in which the various sciences which constitute this field have progressed in bursts brought on partly by new technology and methods. We have seen the greatest flowering of these sciences in our own time, partly owing to the explosive technological growth of the last third of a century and partly, to be frank, because of the space program. The scope of this flowering is best indicated by the wealth of information and theory developed by many investigators and assembled in surveys such as that of Newburn and Gulkis[6] on the outer planets, or Morrison[3] on Mercury.

Let us quickly at this point sum up the capabilities and limitations of Earth-based planetary exploration—what we can and cannot do at the planets without leaving or launching instruments out of Earth's atmosphere. This enables us to characterize what we should and should not attempt through spaceflight. First of all, we can employ massive and bulky instruments—large optical, infrared, and radio telescopes, high-dispersion spectrographs, and the like, which cannot easily be

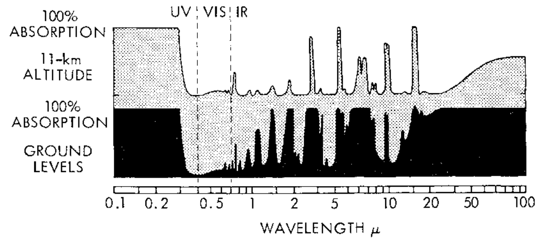

Fig. 3 Spectral windows in Earth's atmosphere at ground and 11 km levels.[29]

launched toward another planet. Second, we can see through the atmosphere over a fair portion of the spectrum of interest (Fig. 3), within seeing limits. Third, we can conduct long-term observations, lasting several nights, many years, even centuries. We can track storms on Jupiter and Saturn, follow clouds on Mars, detect atmospheric constituents on Titan. We can do these kinds of planetary exploration at low risk, in relative comfort, and at fairly small expense. But we cannot look for life on Mars—nor even in fact, map the planet with high reliability. We cannot analyze surface samples from another planet through the telescope. We cannot identify surface features as small as Earth's largest city, so most studies of geology are impossible. We cannot accurately measure nitrogen or the inert gases; oxygen and water vapor are a tough problem because of their abundance in our own atmosphere. Moving further from the target planet, we can infer the existence of a gigantic magnetic field, but we cannot detect a weak one, or determine its absence. We could not detect even our own Van Allen belts, or infer the existence of the complex plasma interaction of our own planet, let alone another's. For these observations, we must go there, or rather, send our instruments.

Thus planetary exploration calls for, and has employed, a team of sciences and technologies. The observatory and the spacecraft are complementary. They have shared instrument designs, data-processing techniques, and personnel. As we shall see, spacecraft planetary exploration has attempted very few experiments that can be done better on Earth. It has rather improved resolution greatly, opened new spectral windows, and used the spacecraft's proximity to or immersion in phenomena which cannot be measured or observed from Earth.

III. The Spacecraft Era, 1960-75

If we were to reflect on and define a rational program for beginning the exploration of the planets with spacecraft, we would likely establish these main points:

1) Begin with targets (e.g. Mars or Venus) which require but do not severely tax the fledgling planetary systems capability and technology. Lunar missions can provide prototype mission experience.

2) Try ballistic flyby first, then orbit the planet, then land.

3) Enhance early mission reliability through multiple attempts in each opportunity.

4) Provide continuous telemetry coverage on early missions to give maximum environmental and failure-analysis data and, if possible, support correction or adaptation for problems.

5) Design the technical systems towards optimum evolution, balancing commonality with adaptibility.

If we evaluate the U.S. and Soviet programs against these "ideal" characteristics, some interesting differences are apparent. Both adopted the first and fifth points; the Soviets ignored Point Two and Point Four but were very strong on Point Three. The U.S. made about half the Mars opportunities and a third of possible Venus launches, to fall short on Point Three (this may reflect relative funding). Each made about the same decision on the tradeoff of energy per unit mass vs launch period. Each appears to have been com-

Table 2 Planetary missions, 1960-74[a]

Year	Mercury	Venus	Mars	Jupiter
1960			Un, 10/10, 10/14 UL	
1961		Un, 2/4 UL; V 1, 2/12 UT		
1962		Ma 1, 7/22 UL; Ma 2, 8/27 F 12/14 Un, 8/25, 9/1, 9/12 UL	Un, 10/24, 11/4 UL; M 1, 11/1, UT;	
1963				
1964		K 27, 3/27 UL; Z 1, 4/2 UT	Ma 3, 11/5 UL; Ma 4, 11/28 F 7/14/65 Z 2, 11/30 UT	
1965		V 2, 11/12 UP; V 3, 11/16 UP; K 96, 11/23, UL		
1966				
1967		V 4, 6/12 A 10/18; Ma 5, 6/14 F 10/19; K 167, 6/17 UL		
1968				
1969		V 5, 1/5 A 5/16; V 6, 1/10 A 5/17	Ma 6, 2/27 F 7/31; Ma 7, 3/27 F 8/5	
1970		V 7, 8/17 A 12/15; K 359, 8/22 UL		
1971			Ma 8, 5/8 UL M 2, 5/19, O&UP 11/27 M 3, 5/28, UP & A 12/2 M 9, 5/30, O 11/31-10/27/72	
1972		V 8, 3/27 A 7/22 K 482, 3/31 UL		Pi 10, 3/3 F 12/4/73
1973		Ma 10, 11/3 F 2/5/74	M4, 7/21, F 2/10 UP M 5, 7/25, 0 2/12 M 6, 8/5, UP 3/12 M 7, 8/9, A 3/9	Pi 11, 4/6 F 12/5/74
1974	Ma 10, F 3/29&9/21			

[a] *Missions:* K = Kosmos (USSR, satellite designator), M = Mars (USSR), Ma = Mariner (U.S.), Pi = Pioneer (U.S.), V = Venera (USSR), Z = Zond (USSR), UN = Unannounced (USSR).
Performance codes: A = atmospheric entry, F = flyby, O = usable planetary orbit, UL = failure in launch phase, UT = failure in transit, UP = failure at planet.

mitted to the idea of exploiting common elements in mission requirements to correlate with common hardware elements, though we know very little about the inner workings of the Soviet planetary program. (Much of what we do know has been compiled by the Library of Congress in an excellent series.[7,8]

The Soviet planetary program, explicitly limited to Mars and Venus and oriented strongly toward atmospheric entry and landing, has encompassed far more launches than the American one; they have apparently tried for every Mars opportunity since 1960 except the 1966-67 and 1969 launch opportunities, and every Venus opportunity from 1961 through 1972, with as many as four launches in a single period. The U.S. program has involved one or two launches each in three Venus and three Mars opportunities. All known planetary launches are listed in Table 2.

The United States, in cooperation with technical agencies of friendly foreign governments, was able to establish deep-space tracking stations around the globe, permitting us to track and communicate with our spacecraft continuously through the mission, with the result that no deep-space problem has yet disabled a U.S. planetary mission. An additional value of this policy is the acquisition of long-period data on interplanetary fields and particles, as an ancillary to the planetary-exploration objectives. Extending this reasoning, U.S. spacecraft systems have been designed for increasing flexibility, through the development of Earth/space control and programable flight-sequence generators on the spacecraft, so that complex planetary operations may be altered or completely rewritten after launch. This flexibility, broadly viewed, permits recovery from accidental damage and improvement of remote-sensing programs on the basis of new data, as in the case of Mariner 7 in 1969. It made possible the complete reordering of the Mariner 9 mission in 1971-72, both to accommodate the great Martian dust storm and to add the observations intended for Mariner 8. In addition, on successive orbits of Mariner 9, observation programs were designed and modified on the basis of data just acquired and interpreted. More recently, the scientists associated with Mariner 10 (1973-74) conducted repeated observations of the Earth and Moon for calibration of Venus during the swingby and of Mercury during successive dark-side and southern bright-side passes with some adaptaive control and major program changes for the multiple, different targets. A very different mode of adaptation, relying on Earth-based control and radio-command activation, allowed the retargeting of Pioneer 11 for Saturn via Jupiter swingby just a short time ago.

In the beginning, the United States was relatively slow to make available large and powerful launch vehicles to unmanned missions, so that virtually all U.S. planetary missions have been weight-limited. This has encouraged a conservative approach to mission objectives (fly-by before orbiting) on the one hand, and considerable ingenuity in component miniaturization and system integration on the other, encouraging in turn a strong emphasis on technology development. The relatively open and pluralistic nature of American society and government institutions and the commitment to a nonmilitary space program has affected our planetary program directly. The participation of scientists from beginning to end in the missions—as responsible experimenters—and the requirement for open publication have

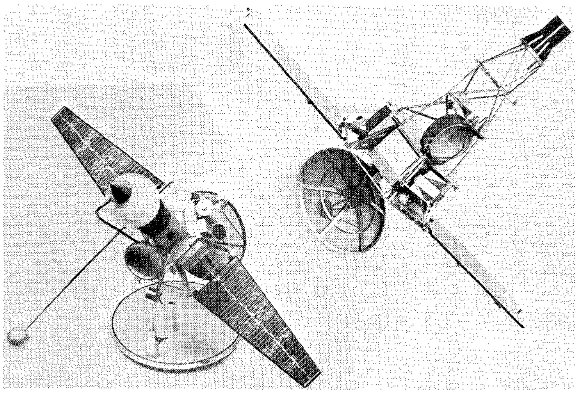

Fig. 4 Comparison in configuration between the Ranger 3 lunar (left) and Mariner 2 planetary (right) spacecraft.

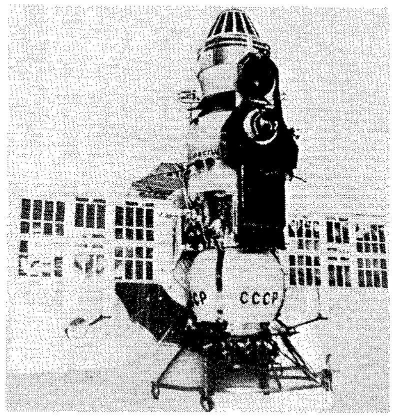

Fig. 5 Typical USSR planetary spacecraft (Venera 5), with atmospheric entry capsule below and reflector antenna behind solar panels.

assured a high quality of scientific work. Before we assess the experience and achievements of spacecraft exploration of the various planets, let us examine the early planetary projects and missions. We will find that the patterns for later work were set in the early attempts, whether or not they were consummated or successful.

A. The Pioneering U.S. Planetary Explorers

The early Mariner planetary and Ranger lunar projects had a common conceptual ancestor in Project Vega, a combined launch-vehicle and flight-mission program, which was partly developed and then cancelled before the 1960's. Envisioning Mars and Venus fly-by missions as well as lunar flights in the early 1960's, and based on a never-flown launch vehicle similar in performance to the Atlas/Agena B, this effort was as ambitious in its way as the early Soviet lunar and planetary program.

Vega gave way to an Atlas/Agena-based lunar spacecraft project, Ranger, and Atlas/Centaur-based Venus and Mars missions targeted for the 1962 and 1964 opportunities. Delays in Centaur development forced the creation of Agena-based planetary projects, which eventually resulted in the Vega-scale Mariner 2 and Mariner 4 missions. These projects accepted extreme restriction of spacecraft mass. The Venus spacecraft configuration resembled the Ranger lunar spacecraft, but weighed only 60% as much at launch. The two spacecraft are shown in Fig. 4; characteristics of several early craft are compared in Table 3. In the meantime, the Ranger project experienced severe difficulties with launch vehicle performance and reliability, spacecraft reliability, and various environmental factors, but still was able to demonstrate, step by step, key functions and elements essential to a successful planetary mission. In the midst of this learning process, Mariner 2, the second launch of the first U.S. interplantary mission, completed a successful flight past the planet Venus.[9]

Mariner 2 obtained valuable fields-and-particles data over most of its four-month flight from Earth to within the orbit of Venus, made temperature measurements at the planet which confirmed an evolving picture of the thermal environment on Venus, and determined that Venus did not have a magnetic field like the Earth's. But in a larger sense, its real achievement in planetary exploration was to do a complete planetary mission for the first time. Maintaining constant communication with the Earth during the flight, the spacecraft responded correctly to commands, sent back engineering and scientific telemetry, and demonstrated all the functions and capabilities associated with the requirements of a planetary flyby mission. This included acquisition of attitude references, attitude control, interplanetary navigation, long range communications, on-board sequencing, temperature control, and long-term solar-powered operation, as well as the successful operation of seven scientific instruments. Similarly, the Tracking and Data Acquisition and Mission Operations Systems enjoyed their first interplanetary flight experience and honed their skills and the design of their machines and computer programs on a real, relentless, long-lasting series of problems and requirements. Planetary exploration, we found, is an operational task which has to be experienced to be understood.

Concurrent with this American development of a planetary exploration flight capability, which might be described as learning to get the most out of the least launch energy and the fewest launches, the Soviet planetary explorers were charting an entirely different course. They used the Atlas/Centaur-scale booster/sustainer vehicle (called "A" by U.S. observers) which launched the early Sputniks and the first USSR ICBM demonstration of 1957, augmented by a third stage called the "orbital platform" to reach the parking orbit and a fourth spacecraft-mounted stage to inject into the interplanetary transfer trajectory almost a ton of Venera or Mars vehicle. The spacecraft design was divided into an interplanetary carrier and a planetary probe (Fig. 5), carrying the spacecraft bus concept further than U.S. designers ever did in practice. This concept was to be sustained in the later Venera and Mars missions; identical buses would carry alternative camera packages or landing probes. However, up to the mid-1960's mission success eluded the Soviet planetary program, despite more than a dozen apparent launch attempts. Difficulties with the launch vehicle system (not unlike those which hampered

Table 3 Comparison of early planetary spacecraft

Name	Venera 1	Mars 1	(Ranger III)	Mariner II	Mariner IV
Intended mission	Venus impact (?)	Mars impact (?)	Lunar impact	Venus flyby	Mars flyby
Launch date	2/12/61	11/1/62	1/26/62	8/27/62	11/28/64
Injected mass, kg	640	900	330	205	260
Flight experiments (number)	(?)	6 (?)	4 (including survival capsule seismometer)	7 (including 2 exclusively Venus-oriented)	9 (including 2 exclusively Mars-oriented)
Performance	Venus flyby (inert), 5/19/61 100,000 km	Mars flyby (inert), 6/63, 192,000 km	Missed moon 1/28/62, by about 32,000 km	Venus flyby (active), 12/14/62, 34,700 km	Mars flyby (active) 7/14/65, altitude 9,800 km

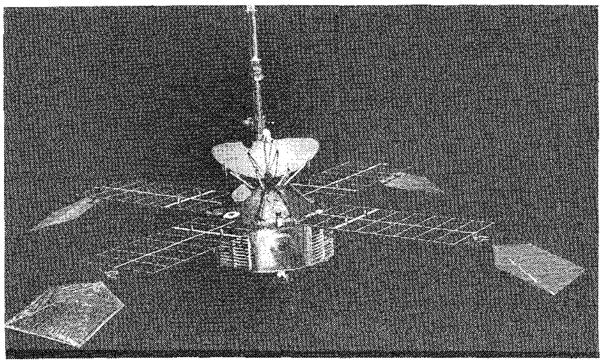

Fig. 6 Mariner 4 Mars flyby spacecraft configuration. TV camera mounted below, magnetometers on mast behind elliptical dish antenna.

the U.S. Ranger project and aborted the Mariner 1 and Mariner 3 launches) and disabling spacecraft failures (which also occurred on Ranger missions) coupled with the all-or-nothing planetary landing objectives and restricted spacecraft tracking arrangements, were apparently too much for the state-of-the-art of the time.[7,8]

The first successful Mars mission, the U.S. Mariner 4, began in November 1964. It faced new and increased requirements. The flight life must be at least eight months to Mars encounter. Solar radiation, the spacecraft energy source, would decrease during the flight to less than half the Earth-orbit value per unit area, instead of doubling as on the Venus mission. Communication distance would be greater (215 million km at encounter, compared with about 80 million for Mariner 2). A television camera, and the means to point it and record and transmit its pictures, was a necessity for the Mars mission. For a Mars mission, the spacecraft (Fig. 6) would have to base its attitude control on stars—the Sun and Canopus—instead of using the Sun and the Earth. For meeting all these needs, and mounting a new and larger scientific payload, Mariner could have a small increase in spacecraft weight over the Venus spacecraft—260 kg, compared to about 200 kg.[10]

The Mariner 4 mission proved to be a dramatic, practical, and scientific success, with the Mars flyby on July 14, 1965

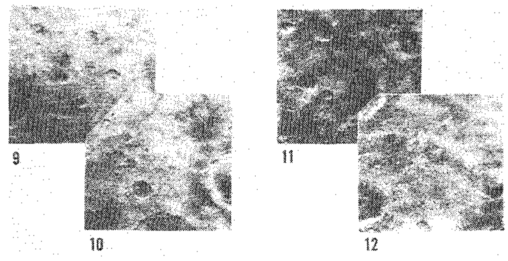

Fig. 7 Four of the 22 images of the Mars surface obtained by Mariner 4 in July 1965.

yielding important new data about the planet. Among the scientific "firsts" of this mission were the crater-revealing television images and radio-occultation measurements of the 6-millibar atmospheric pressure. The 22 pictures covered less than 1% of Mars' surface, but they had a powerful impact on our view of the planet. With this mission, the pioneering phase of planetary exploration (summarized in Table 3) is succeeded by the operating phase. For other kinds of planets and other kinds of missions, some pioneering continued, as in the case of Pioneer Jupiter for example, and the Venera 8 landing. But Mariner 4, the first spacecraft to challenge Earth-based planetary exploration and add significantly to our data on another planet, was also the definitive answer to the question of whether the space project was capable of taking a major role in planetary science.

B. Mars: The First-Priority Planet

The Mariner 4 mission in 1965 brought forth a new view of the planet Mars as a rather moon-like object, its surface an old, cold, cratered desert (Fig. 7), its atmosphere extremely thin and dominated by carbon dioxide, its magnetic field negligible and its interior seemingly inert. This was a stark contrast with earlier speculations and science fiction, though roughly in line with the evolving trend of a few Earth-based observations. Ironically, this view of Mars was to last only a handful of years. The story of Mars exploration over the past decade (Table 4) is a model of planetary exploration in many ways. There is the series of progressively more sophisticated missions, which is still developing; the introduction and impact of new techniques; and the interplay between Earth-

Table 4 Mars missions, 1964-74

Mission name	Launch—Arrival	Mission plan	Remarks
		1964 opportunity	
Mariner III	11/5/64—N/A	Flyby	Disabled at launch
Mariner IV	11/28/64—7/14/65	Flyby	Returned TV pictures, occulation data, fields and particles measurements, continued operating until 12/20/67
Zond 2	11/30—N/A	Unknown	Communications failed in April 1965, flew by Mars (inert) on 8/6/65
		1969 opportunity (no Mars launches in 1966/67)	
Mariner 6 and Mariner 7	2/27/69—7/31/69 3/27/69—8/5/69	Flyby	Payload concentrated on planet; took distant and closeup TV pictures, analyzed atmosphere, south polar cap, etc., operated after Mars encounter through 1970
		1971 opportunity	
Mariner 8	5/8/71—N/A	Orbiter	Destroyed at launch
Mars 2	5/19/71—11/27/71	Orbiter/Lander	Good orbit (1380×25,000 km); capsule apparently failed
Mars 3	5/28/71—12/2/71	Orbiter/Lander	Poor orbit; capsule landed, began TV transmission, failed. Technical failures virtually destroyed scientific value. Mars 2 orbiter imaging (film system) completed sequence before dust-storm abated.
Mariner 9	5/30/71—11/13/71	Orbiter	Mapped the planet, returning 6878 TV pictures, myriad IR and UV spectra, IR temperature measurements, occultations. Operated until 10/27/72.
		1973 opportunity	
Mars 4	7/21/73—2/74	Orbiter	Failed to enter orbit
Mars 5	7/25/73—2/74	Orbiter	Obtained pictures from elongated orbit
Mars 6	8/5/73—3/74	Lander	Unsuccessful atmospheric entry
Mars 7	8/5/73—3/74	Lander	Entered atmosphere, failed on landing

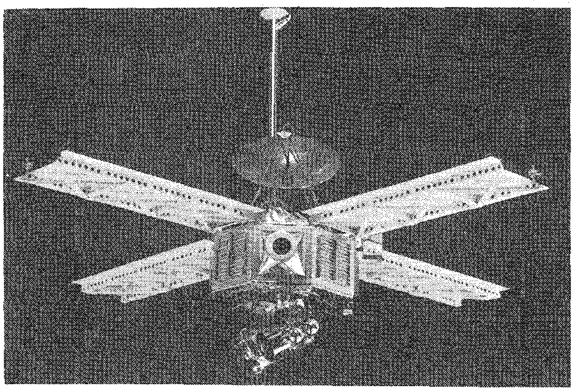

Fig. 8 Mariner 6 and 7 Mars spacecraft configuration, with two-degree-of-freedom scan platform carrying two TV cameras, IR radiometer and spectrometer, and UV spectrometer.

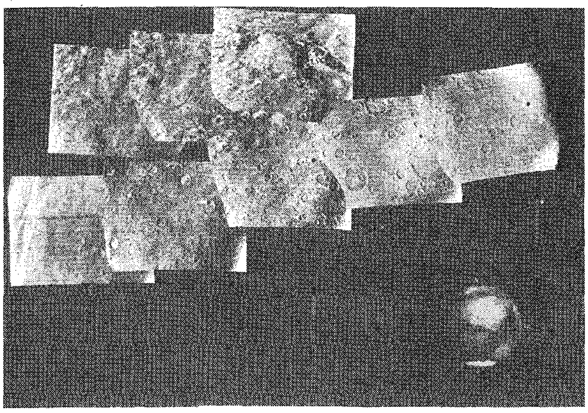

Fig. 9 Mosaic of wide-angle frames taken by Mariner 6 in 1969, with approach picture showing frame placement on Mars.

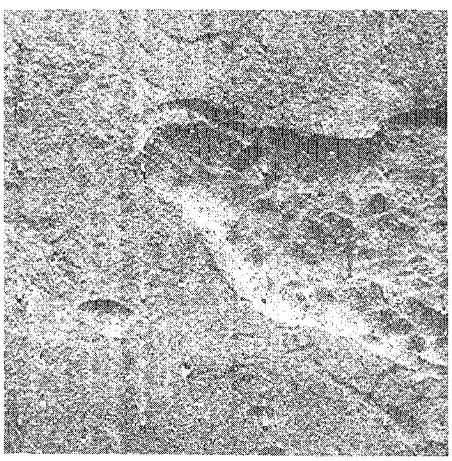

Fig. 10 Portion of a Mariner 6 narrow-angle frame, indicating "chaotic" terrain features.

based and spacecraft observations, and between successive missions.

A striking new technique in planetary exploration, developed and demonstrated in the Mariner Mars 1964 project, is radio occultation measurements of atmospheric density. This measurement was desired not only by the planetary scientists but by the engineers beginning to design Mars landing capsules. It is mechanized by using the spacecraft radio tracking signal (no special flight equipment), and flying the spacecraft behind the planet (as seen from Earth). This technique was conceived shortly before the 1964 launch by D. L. Cain of JPL who had been studying the effects of atmospheres on the propagation of tracking signals. It occurred to him that this relationship was reversible: the

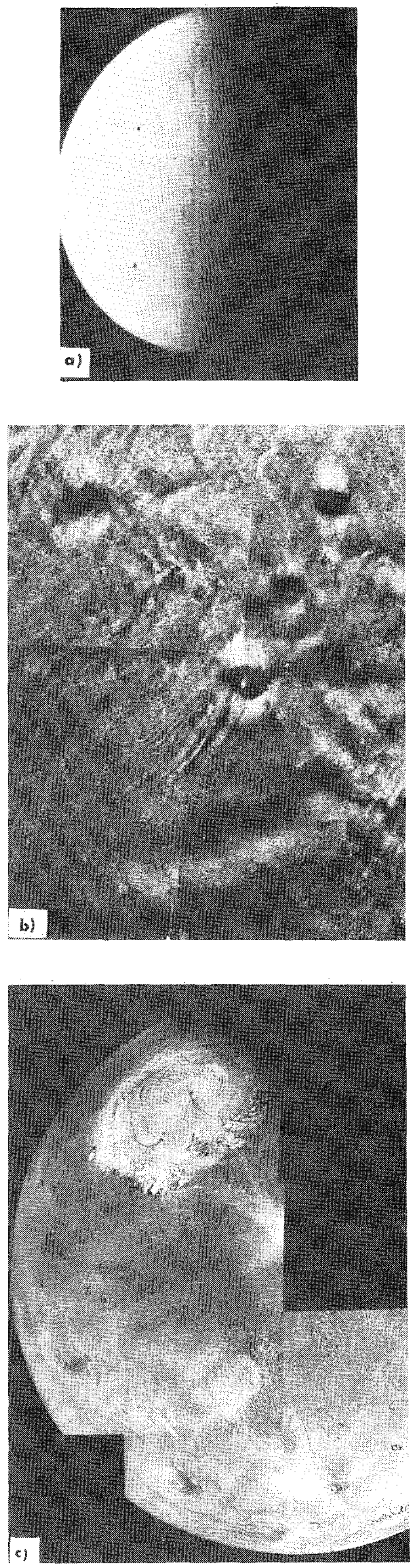

Fig. 11 Effects of great Martian dust storm as recorded by Mariner 9. a) In the approach picture, virtually no surface detail is apparent. b) The closer-range mosaic, after intensive computer processing, reveals the tops of four giant volcanoes rising above the dust clouds. c) The final mosaic, taken from about 14,000 km range long after the storm had abated, shows a variety of terrain from the north polar cap past the same four volcanoes to a part of the Martian Grand Canyon.

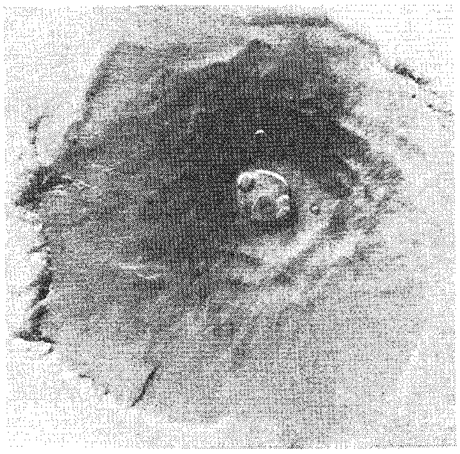

Fig. 12 The largest known volcano, Mons Olympica on Mars, shown in a computer-processed Mosaic of Marine 9 images obtained in January 1972. The mountain is 600 km across at the base, about 23 km high.

neutral atmosphere could be measured by its propagation effects. Cain, T. W. Hamilton, and A. Kliore quickly began to study whether the radio frequency stability was good enough for such an operation, and how sensitive the beam would be to a low-density atmosphere and to ionospheric effects.[11] JPL had been developing highly stable oscillators for radio tracking; this capability seemed to support an occultation measurement. Finding the experiment feasible, they proposed it to the Mariner Project. V. R. Eshleman, who had earlier proposed a radio investigation of charged particles in Mars' inosphere, joined the experiment team.

It was no easy matter to persuade the Mariner Project Manager to voluntarily relinquish communications and control links to the spacecraft during the latter part of the critical encounter phase, before the TV pictures of Mars had been played back and received. However he agreed, and this technique, sometimes augmented by multiple-frequency equipment, has been a part of every subsequent U.S. planetary mission where it was possible. The Mariner IV occultation experiment correlated well with the TV pictures to produce the bleak model of Mars which prevailed for the next few years.

Mariner 6 and Mariner 7 were advanced Mars flyby spacecraft (Fig. 8) which obtained higher-resolution pictures and covered about 10% of the surface, together with sets of full-disk images obtained on the approach (Fig. 9). They also acquired infrared and ultraviolet spectra giving compositional data on the atmosphere, and surface-temperature profiles down to the polar cap and across the terminator.[12] This dual flight mission confirmed that the polar covering was solid CO_2 (as proposed on the basis of Mariner IV data) over an inferred small mantle of ice, and established CO_2 dominance in the atmosphere, with no detection of nitrogen. A few pictures on the edges of the area observed at high resolution indicated quite different terrain types from predominantly cratered regime (Fig. 10). The major technology advances of this project (e.g., high-resolution remote sensors, programable flight-sequence controller, and high-rate communications) made the subsequent orbiting mission possible.

At the 1971 opportunity, both U.S. Mariner and USSR Mars planetary orbiters were established. During the transit flight, Earth observers watched a large-scale dust storm develop and occlude the entire planetary surface. As Mariner 9 approached and entered orbit, a completely blank globe appeared to its television telescopes. Fortunately, the Mariner spacecraft design had incorporated a programable computer since 1969, and the spacecraft and the mission's scientists could wait the three months while the storm gradually ebbed, revealing level by level the remarkable topography of Mars (Fig. 11). The unique capability of the digital television system

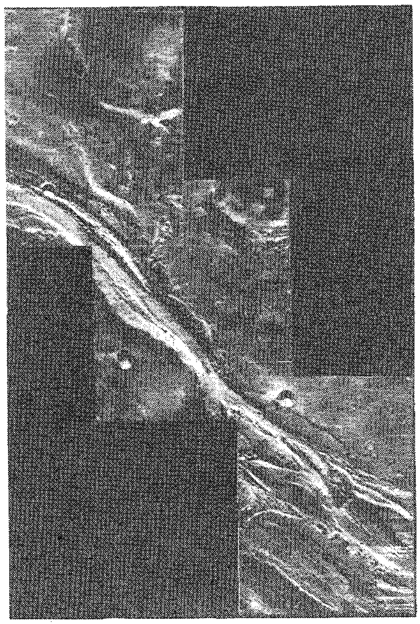

Fig. 13 Sinuous channel believed carved by running water on Mars, imaged by Mariner 9 in July 1972.

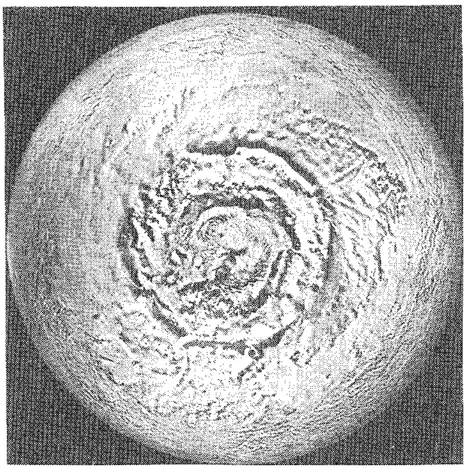

Fig. 14 Polar view of photomosaic globe of Mars shows complex structure of the north polar region.

for discriminating scene brightness variations, and sophisticated techniques for computer-processing the returned images, made it possible to bring out contrast detail invisible to the eye in the raw picture. Unfortunately the Soviet Mars 2 orbiter had a fixed program and a film-recording system, and it was constrained to film Mars before the surface became completely visible.

The prospect of Mars revealed by the Mariner 9 orbiting observer in almost a year of operation was as striking as it was different from the first Mariner view of the planet. Evidences of geological and meteorological activities abounded. First to appear as the dust settled were the gigantic shield volcanos of Nix Olympica (seen from Earth and Mariner 1969 pictures as a white spot and shown in a Mariner 9 composite image, Fig. 12) and the W-cloud region. Sweeping in a great 4000-km area west of the cratered zone observed earlier was a deep, broad rift valley with complex tributaries. Some channels gave impressive evidence of having been formed by fluid runoff, resembling terrestrial river beds (Fig. 13). Other features bore signs of wind erosion. As the polar caps sublimed with the turn of the seasons, they revealed partly eroded structures of many layers (Fig. 14). The overwhelming impression was that of an active geological history which had changed parts of Mars' surface drastically since the era of impact cratering, while other regions still showed the marks of that ancient

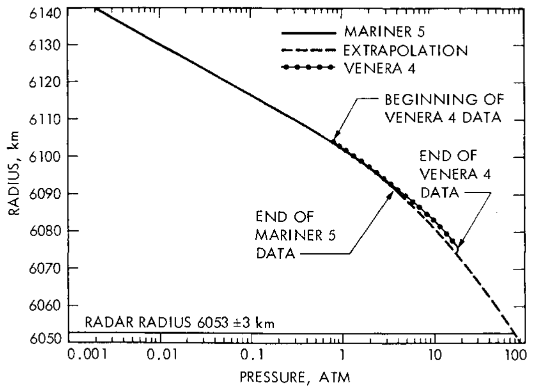

Fig. 15 Atmospheric pressure profile of Venus using Mariner 5, Venera 4, and Earth-based radar data obtained in October 1967.

bombardment.[13] The idea that water had been an active agent in the planet's history, and might still be present as permafrost and polar-cap substrate, gave new hope to the search for signs of life on Mars. Interpretation of data from the Mars 2 and 3 missions of 1971 and the USSR Mars missions of 1973 tend to confirm this radical revision of our view of Mars.

C. Venus: The Clouded Picture

The exploration of Venus does not represent the kind of evolutionary enlightenment we have seen at Mars. For one thing, the atmosphere is always as opaque as the great Mars dust storm. The surface has never been seen, though significant parts have been observed and imaged with Earth-based radar. Many of the significant discoveries about Venus have been made during the space age by Earth-based measurements, in fact, as discussed previously.

The first Mariner Venus mission, Mariner 2, did establish in 1962 that Venus' magnetic field was negligible. The first three Venera spacecraft failed prior to encounter, though Venera 2 flew by the planet in late February 1966 and Venera 3 made an impact on March 1. The real spacecraft-experiment breakthrough came in 1967, with the combination of Earth-based radar measurements with experiments performed on the Mariner 5 and Venera 4 missions. It was at this time that the high temperature and pressure of the lower atmosphere were established.[14] Confirmation of these conclusions came with subsequent missions.

Venera 4, consisting of a spacecraft carrier and landing capsule,[8] arrived at the planet on October 18, 1967, the day before the Mariner 5 flyby. The capsule was apparently designed for a less dense, cooler atmosphere than Venus turned out to possess. It entered the atmosphere on the night side, near the sub-Earth point, deploying a parachute on a signal from a radar marker altimeter indicating an altitude of approximately 26 km (in fact, this must have occurred at double the intended altitude). It then descended through the lower atmosphere for 90 minutes, conducting gas analysis at two points and returning density, pressure, and temperature measurements until the sensors and finally the capsule stopped transmitting, at an indicated temperature of 544 K and an extrapolated pressure of some 18 atm (last measured pressure being 7 atm).

The next day Mariner 5 flew by,[15] conducted a dual-frequency occultation experiment from which atmospheric properties were derived down to the super-refractive point, at a radius of about 6085 km from planet center. Good agreement between the pressure and temperature curves from the two missions was found over an overlap, which placed the Venera 4 termination, interpreted for some time as a surface landing, at a radius of 6075 km. Earth-based radar measurements from a number of radar observatories, including observations from Arecibo made on October 19, indicated a radius to the planetary surface of 6050 to 6056 km. Extrapolating the temperature and pressure curves from spacecraft data to this region yielded a surface temperature of about 700 K (in general agreement with Mariner 2 and Earth-based microwave measurements) and a pressure of about 90 atm (Fig. 15). These data were in fact confirmed by the Soviet scientists after the Venera 5 and 6 missions of 1969, and the Venera 7 and 8 landings in 1970 and 1972 (Table 5).

Other spacecraft discoveries have included a relatively close plasma interaction with the detached bow shock (Fig. 16), observed in 1967 and again by Mariner 10 in February 1974. The latter mission, which used a close passage by Venus to propel it on to Mercury, also observed a long and active magnetic

Table 5 Venus missions, 1967—1974

Mission	Launch—Arrival	Mission plan	Remarks
		1967 opportunity	
Venera 4	6/12/67—10/18/67	Lander	Parachuted through atmosphere for 90 min, direct gas analysis, pressure, temperature, etc., terminated at 25 km altitude
Mariner V	6/14/67—10/19/67	Flyby	3946 km closest approach; fields and particles, remote measurements of upper atmosphere, dual frequency occultation probe of atmosphere
		1969 opportunity	
Venera 5	1/5/69—5/16/69	Lander	Both capsules entered atmosphere, parachuted for 50 min;
Venera 6	1/10/69—5/17/69	Lander	similar experiments to Venera 4, carried to lower levels (measured pressure 27 atm)
		1970 opportunity	
Venera 7	8/17/70—12/15/70	Lander	Capsule landed and survived 23 min with reduced signal strength; surface temperature 455-495°C, pressure 75-105 atm
		1972 opportunity	
Venera 8	3/27/72—7/22/72	Lander	Capsule landed and survived 40 min; gamma-ray spectrometer analyzed U, Th, and K in surface minerals
		1973 opportunity	
Mariner 10	11/3/73—2/5/74	Flyby	5785 km flyby enroute to Mercury. TV pictures (near-UV) of atmospheric structure for 8 days; mapping of plasma interaction, occultation probing of atmosphere

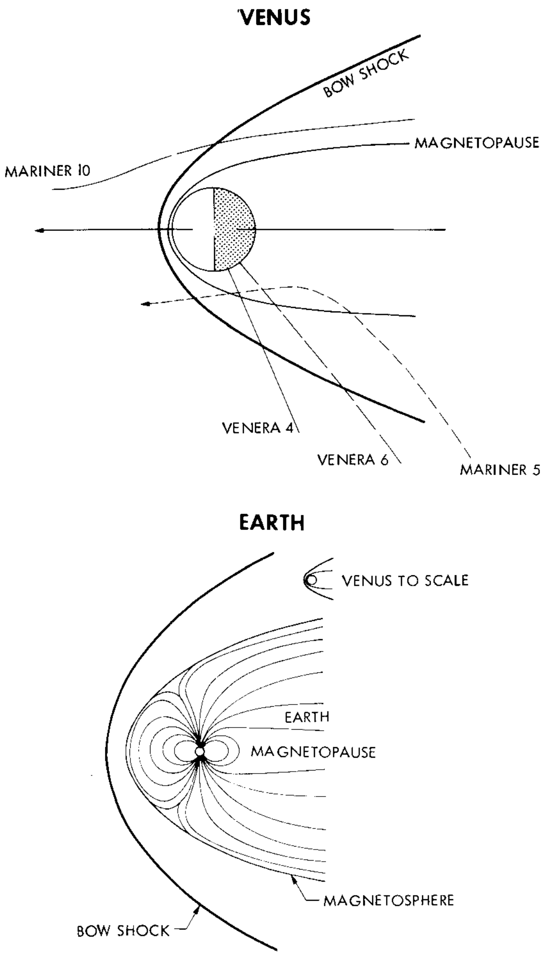

Fig. 16 The magnetosphere of Venus, as observed by Mariner 5 and 10 and Venera spacecraft (above) compared with the more extensive and complex magnetosphere of Earth (below).

Fig. 17 Retouched mosaic of ultraviolet images of the clouds of Venus obtained by Mariner 10 in February 1974. The equator-to-pole spirals emanate from the subsolar point, left of center.

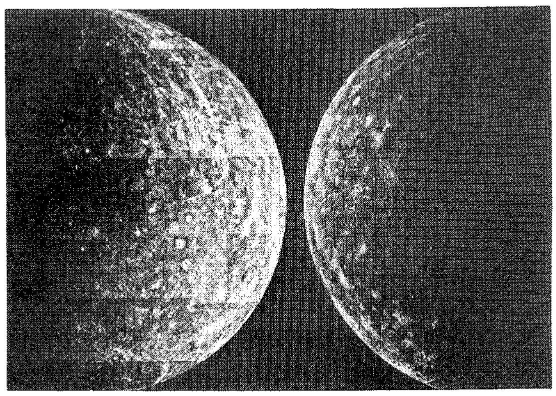

Fig. 18 Incoming (right) and outgoing (left) views of the planet Mercury, each constructed from 18 frames obtained by Mariner 10 on March 19, 1974.

and charged-particle tail streaming out in the antisolar direction. In addition, Mariner 10 obtained many mosaics of images, particularly in the near ultraviolet, which resolved atmospheric features and obtained a history of atmospheric dynamics over several days. The Y-shaped marking, observed faintly from Earth, was resolved into a complex structure (Fig. 17) indicating classical equatorial-to-polar circulation, and many features of the four-day rotation of the upper atmosphere were revealed.[16]

Thus in contrast to the exploration of Mars, which is dominated by the study and mapping of surface features, and surface dynamics, spacecraft exploration of Venus has been dominated by the study of atmospheric and plasma-interaction properties. Mapping of the solid surface has been done from Earth, where the powerful and sensitive radar telescopes are; spacecraft television observation, useful only in the ultraviolet and showing only atmospheric features, began effectively only in 1974. Physically probing the atmosphere down to the surface has been a monumental technical achievement on the part of the Venera program, but has so far yielded relatively little new information.

D. Mercury: A Beginning, Two for One

The planet Mercury is among the most difficult to observe from Earth because of its constant proximity to the Sun in our skies. It is also relatively difficult to reach by spacecraft, requiring almost as much launch energy as a flight to Jupiter. Thus it was natural that an attack on some of the perplexing questions posed by this hot little world was put off, in favor of less difficult and possibly more rewarding targets, until last year's Venus swingby opportunity. It was also natural that the first close-up measurements of Mercury would fill in large gaps in our knowledge of the planet and of the family of terrestrial planets.

The technique of reaching Mercury in the Mariner 10 mission of 1973-74 was one which had been studied for some time, and which, now that it is proven, opens up a variety of planetary missions. It is gravity assist: the use of an available gravitational field to work a significant energy change, using a precisely navigated close flyby. The Mariner 10 flybys of Venus, at an altitude of about 500 km above the surface, changed the spacecraft velocity by more than a kilometer per second, making the Mercury flyby possible. In turn, the Mercury pass seven weeks later at an altitude of about 1000 km, turned the flight path into a unique orbit (originally recognized by Giuseppe Colombo) which is resonant with that of the planet, so that repeated flyby passages occur about every six months.

The first Mercury encounter, at the end of March 1974, had to be a night-side passage, with solar as well as Earth occultation. This permitted a cross section of the plasma interaction by the fields and particles sensors, and a sensitive spectral search for atmospheric constituents using transmitted sunlight in the brief intervals going into and emerging from solar occulation. It also made possible surface-temperature scans around the planet in day and night.[17] This flyby geometry slightly limited the resolution and coverage of TV imaging, especially in the subsolar region. The second flyby, in September, was made over the southern sunny side at a sufficient altitude not to distort the harmonic orbit, filling out the television coverage of the lighted hemisphere with a south-polar survey. The third, in March 1975, clearly identified Mercury's intrinsic magnetic field with a very close flyby.

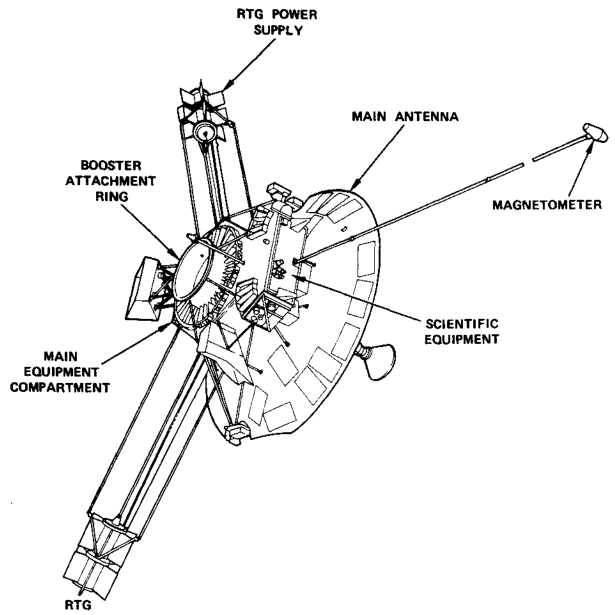

Fig. 19 Pioneer 10 and 11 spacecraft configuration.

Because of the paucity of Earth-based data on Mercury (due to observational difficulties), Mariner 10 contributed a majority of what we now know about the planet—a situation only rivaled by the several missions to Mars. One of the most important new undertandings arises from the character of Mercury's surface and its known bulk density. The television pictures revealed a surface strongly resembling the moon: heavily cratered and rayed regions, mare-like volcanic plains, etc. (Fig. 18). But the bulk density of the moon is 3.3 g/cm, vs a confirmed 5.4 for Mercury. The planet cannot be, as the moon is believed to be, moon-like all through: it must have a dense metallic core like the Earth. Our planet retains virtually no visible evidence of the four-billion-year-old cratering process; its original surface has been erased, partly by atmospheric and water effects, and partly, it is believed, by the long, slow process of differentiation into core, mantle, and crust. Mercury's history must have been vastly different from this picture: could it have accreted in such a way that heavy metallic phases condensed first, followed by silicates? This possibility of orderly creation of a planet could have profound implications for our thinking about the history of the solar system.[17] The unexpected magnetosphere observations add to this process, both for the origin and evolution of Mercury and, perhaps, for our theories of planetary magnetism. Mercury's tenuous helium atmosphere, whose source may be the sun or radioactive decay within the planet, also supports new speculations. The first step in the exploration of Mercury has thus been a large one, not only in achieving multiple passages by the planet and in acquiring large amounts of new information but in the importance of the scientific ideas born of the mission. This is a solid indication not only of the maturity of our planetary exploration ability but of the great opportunities which are waiting for explorers of the untraveled regions of the solar system.

E. Jupiter: Lifting the Curtain

Exploration of the larger bodies of the solar system has begun with two Pioneer flyby missions, one encountering Jupiter in early December 1973[18] and another a year later. This project has given scientists an early close-up look at the largest and closest member of the outer solar system, while serving as pathfinder for later, more comprehensive outer-planet missions.

This step was made possible by a technology transfer somewhat like that which brought about the first successfully planetary mission in 1962, the Mariner 2 Venus encounter, which was derived in major parts from lunar-mission technology. The Pioneer program was previously based on simple, lightweight, spin-stabilized spacecraft placed in heliocentric orbits for the extended study of the interplanetary medium. The 65 kg solar-powered spacecraft carried half a dozen fields-and-particles experiments. The first of this series, Pioneer 6, was launched over nine years ago; all four of the series are still functioning in orbits between 0.8 and 1.125 a.u.

For the mission to the outer solar system, the Pioneer configuration had to grow considerably. The 259 kg spin-stabilized spacecraft (Fig. 19) uses radioisotope thermal electric power and a high-gain reflector antenna. Its 33 kg payload of 11 scientific instruments retains a strong emphasis on fields and particles, which the addition of photometric and radiometric instruments in the visible, infrared, and ultraviolet.

In their transits of the Asteroid Belt and the Jupiter regime, these missions have given us the data to model the space flight

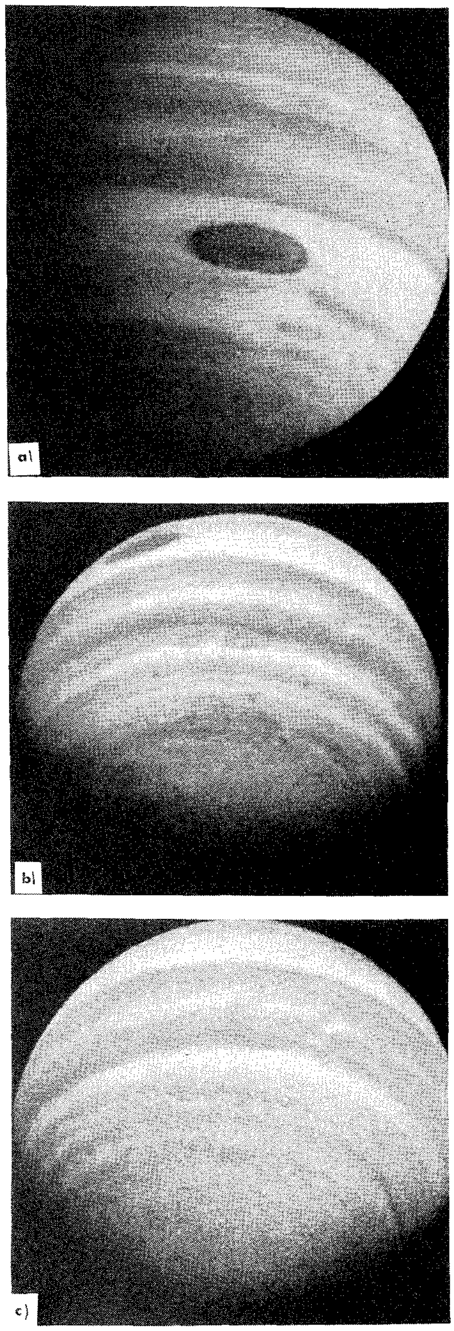

Fig. 20 Three images of Jupiter (originally in color) reconstructed from data obtained by the Pioneer 11 photopolarimeter in December 1974. a) The Red Spot is prominent in the approach view; b) and c) are the two south-polar flyby views.

environment for future outer-planet missions, particularly the planned Mariner Jupiter/Saturn 1977 endeavor. They have settled our concerns about the particle-impact possibilities en route to Jupiter, and have charted the intense charged-particle zones which surround that planet, a special concern of Jupiter mission planners. Pioneer 10's measured values of high-energy electron flux, for example, turned out to be about three orders of magnitude above Earth-based estimates. This represents the achievement of one major objective of the mission. The second objective for this first mission to Jupiter was the acquisition of first-hand scientific data on the giant planet itself. Using spin-scan photometers, the two spacecraft provided data resulting in spectacular images of the planet, considerably exceeding Earth-based resolution (Fig. 20). Pioneer 10 was occulted by the satellite Io, and confirmed the presence of a tenuous atmosphere there. Pioneer 11 flew over the south pole of Jupiter in order to take a gravity-assist trajectory towards Saturn. Several fields-and-particles instruments in concert provided data on the magnetosphere and plasma interaction of Jupiter (Fig. 21), which utterly dwarfs the Earth's magnetosphere. Jupiter's magnetic field was found to be offset, tilted relative to the axis of rotation, and relatively planar as well as extremely extensive, so that it swept north and south past each spacecraft rather like an invisible surf, several times during the encounters.

F. The Past Decade: Planetary Exploration Grows Up

In the ten years since the beginning of the Mariner 4 mission to Mars, we have seen planetary exploration reach a prime level of effectiveness. It began as a high-risk enterprise, with relatively limited objectives, in a scientific field characterized by vast unknowns, many speculations, and relatively little public or technical understanding. Launch and flight failures were common. Now, a solid foundation of operational experience and ability has accumulated, and techniques have been invented and improved to a high level of sophistication.[19] Reliability has increased greatly, as has the degree of technical challenge which can be accepted. The scientific community has become first interested and then adept in the use and integration of this new area and mode of expanding knowledge.

IV. State-of-the-Art of Planetary Exploration

Sections II and III have given considerable evidence of the development of a strong capability to explore the planets of the solar system. The development has continued, as we shall see in Sec. V when we examine U.S. projects which are under development and various opportunities for future missions. In this section let us characterize this dynamic state-of-the-art. Although we have seen that planetary exploration is an interdisciplinary and multinational effort in principle and practice, I am limiting this assessment to the U.S. spacecraft mission technology. We shall examine planetary exploration technology under three broad functional headings: first, matters associated generally with the flight path, which I call simply, "getting there;" second, functions and capabilities of the spacecraft, which I call the remote system; and, third, the Earth-based functions, which constitute the central nervous system of planetary exploration missions. In addition we will consider the integration of functions and the management approach which has evolved.

A. Getting There

There are two crucial skills involved at the outset of any planetary exploration mission, which deal with two basic aspects of ballistic interplanetary flight. The first is to give the spacecraft sufficient velocity to leave Earth and reach the vicinity of the planet; the second is to navigate the spacecraft to its desired target zone above, around, or on the planet.

To send a spacecraft to another planet, it is necessary to alter the spacecraft's velocity from that of the Earth. The farther the spacecraft is to go in or out from the Earth's orbit, the larger the change in velocity. We must select trajectories which require the minimum practical velocity change to stay within the payload capabilities of reasonable launch vehicles. For direct transfers from Earth to a target planet, the interval between launch opportunities is 4 months for Mercury, 19 for Venus, 26 for Mars, 13 for Jupiter, and essentially 12 months for the planets beyond Jupiter, which orbit relatively slowly (in angular terms).

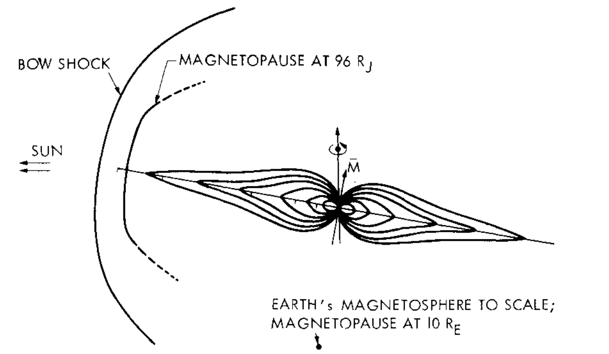

Fig. 21 The magnetosphere of Jupiter, from Pioneer 10 data obtained in late 1973. Earth's magnetosphere is shown to scale.

Four launch vehicle families are applicable for planetary-class missions, three current systems and the Space Transportation System, expected to be in operation about a decade from now. The three current launch vehicle families utilize military missile designs for first stages (Thor, Atlas and Titan). A Delta second stage is used on the Thor and the Centaur is used on the Atlas and Titan vehicles. A solid-motor kick stage has been added to these launch vehicles for low-mass, high-energy missions. The Space Tug concept has been developed to operate with the Shuttle; it could be operational by 1985. The same solid-motor kick stage can be used on the Tug for high-energy missions. The performances of these launch vehicle combinations are shown in Fig. 22 in terms of characteristic velocity. Characteristic velocity is that velocity delivered at 100 naut miles above the Earth to achieve a given mission. For instance, the velocity to just stay in orbit at that altitude is 7.8 km/sec. Shown at the bottom of Fig. 22 is a range of typical velocity requirements to achieve missions to the planets. Velocity requirements vary for different opportunities due to changes in relative geometry. With the current launch vehicle families it is possible to deliver significant payloads as far out as Saturn, and a minimal payload to Uranus. With the advent of the Shuttle in the early 1980's and the Space Tug by 1985, it will be possible to deliver large payloads to Uranus.

Launch vehicles, however, aren't the only means of altering spacecraft velocity. It was found a decade ago that it is possible to change a spacecraft's velocity by flying close to a passing planet, using the bending of the spacecraft's trajectory about the planet to vectorially add or subtract velocity. The technique was recently used successfully on the Mariner Venus/Mercury flight. The general characteristic of gravity assist applied not only to Mercury via Venus, but to the outer planets via Jupiter. Saturn and Uranus may also be used in going to Neptune and Pluto, but they are not as effective as Jupiter, and are harder to reach in the first place. At the bottom of Fig. 22, flybys to Saturn, Uranus, Neptune, and Pluto via Jupiter are shown, linked to the direct missions. Essentially the launch vehicle supplies sufficient velocity to get to Jupiter and the gravity effect of Jupiter supplies the additional velocity to get the spacecraft out to the orbits of the planets indicated.

Supplying the necessary velocity to the spacecraft is of little use if we can't deliver a spacecraft accurately (in both position and time) to the desired target. Current navigation of spacecraft is accomplished by determining the position of the spacecraft relative to Earth by processing the spacecraft radio signal to give velocity and range data. As the spacecraft gets sufficiently close to the target to sense its gravitational pull, a

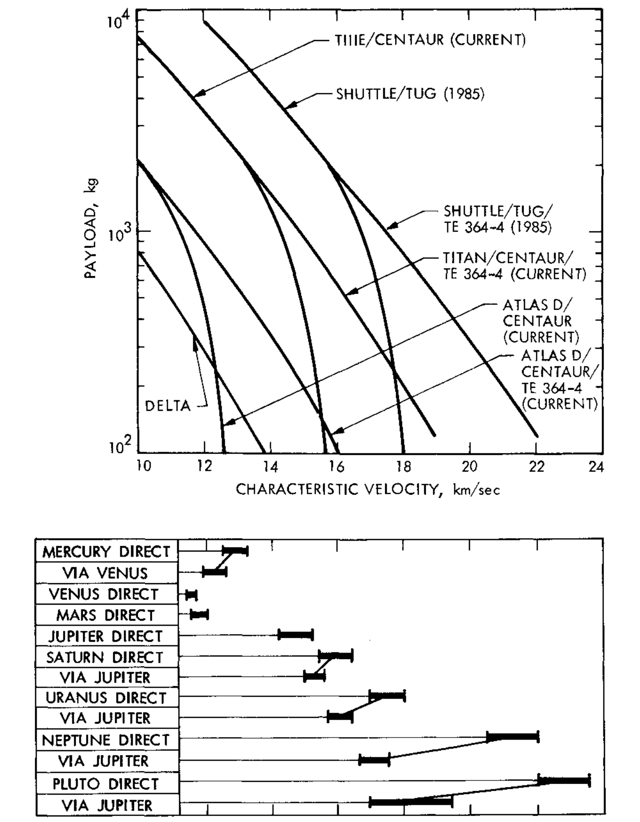

Fig. 22 U.S. launch vehicle performance capability and typical planetary launch requirements.

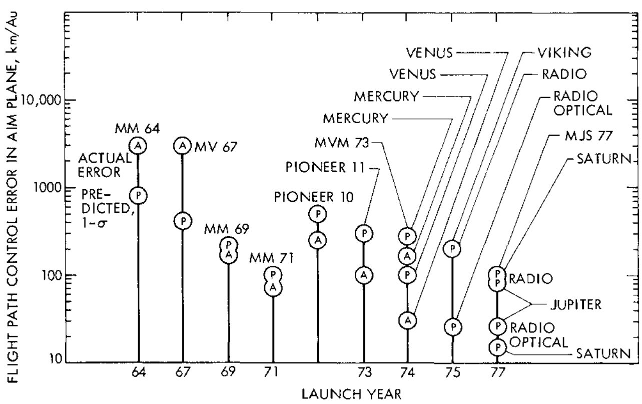

Fig. 23 Improvement in planetary navigation performance, 1964-74, with future performance projections.

Table 6 Mariner 10 navigation results

Target	Flyby distance error, km/%	Arrival time error, sec
Venus	27/0.2	48 (early)
Mercury I	165/4.8	5 (early)
Mercury II	742/1.48	88 (late)

further refinement in the position of the spacecraft relative to the target is possible. Our ability to navigate to a planetary target has steadily increased since Mariner 2 in 1962, as is illustrated in Fig. 23. The recent navigation results obtained from Mariner 10 for its encounter with Venus and two subsequent encounters with Mercury are shown in Table 6.

Radio-tracking navigation has become a very powerful tool in the inner solar system. However, for outer planet missions where distances are much greater and the positions and motions of target planets and satellites are not known so accurately, it is desirable to include additional navigation capability. One promising approach uses the spacecraft's television camera to take planet and satellite images against a known star background. This optical navigation was flown experimentally on the Mariner 9 and 10 flights. Combined with radio tracking, this navigation capability will allow outer-planet missions to achieve navigation accuracies as good as those currently obtainable at the inner planets. The 1977 Mariner Jupiter/Saturn mission will use this navigation combination to achieve its precision mission objectives. The entire art of planetary navigation, past and future, has been recently surveyed by Kohlhase.[20] In summary, we have at present the capability to deliver reasonably massive spacecraft with reasonable accuracy to meet the objectives of any reasonable mission likely to be required in the next decade or so. We are also evolving a capability to meet the launch energy and navigation requirements likely to develop beyond that period.

B. The Remote System

Planetary exploration as I view it is carried out using spacecraft designed on the basis of mission objectives balanced by technical capabilities. We try to balance autonomy and responsiveness or adaptability in such a design. We have seen in the discussion of past missions (Sec. III) the adaptation of system concepts and subsystem designs from one type of mission to another, as well as fundamental changes resulting from new objectives and capabilities. We shall see such relationships in the future. We have also seen, in the experience of prior missions, the value of a degree of autonomy and the great advantages of flexibility and adaptiveness. The principal functions of this system are to acquire specific scientific data at the planet (and otherwise as required), process the transmission, and transmit the data to Earth. These functions impose general requirements on the spacecraft, such as the orientation and control of the scientific sensors, the maintenance of appropriate thermal and other environmental conditions, and other maintenance functions such as electrical power supply, antenna and reference orientation, data handling and storage, communications, and the like.

Similar requirements have existed for earth-orbital missions, from which many planetary exploration techniques and designs have evolved. Among the inner planets, including Earth, solar energy is the chief source of power. However for outer-planet missions, the increased solar distances require a change in power source, specifically to the use of heat from radioactive decay to drive a thermopile. In addition, the increased communication distance to Earth required by planetary missions has imposed new requirements on transmitting equipment and, because of the concomitant increase in round-trip response time, on command and control equipment as well. A significant portion of the increased capability to do planetary exploration has been made in Earth-based systems, which are discussed later in this section. However considerable progress has been made in spacecraft design. It should be noted that a significant impulse toward the advance of communications systems has come through increasingly demanding mission objectives, from scientists interested in increased data rates, particularly those associated with imaging instruments. Communications improvements have resulted from higher-power spacecraft transmitters, the precise orientation of narrower-beam antennas, and the use of higher frequencies. Spacecraft now being prepared and developed employ S-band and X-band, transmitters as powerful as 30 w, reflecting antennas as large as 3.66m in diameter, and data rates as great as 115,200 bits/sec from Jupiter. The evolution of this capability is shown in Fig. 24.

In command and control, spacecraft equipped with programable computers and science and engineering data-processing systems have been evolved. Sufficient computer memory capacity can be employed to store, and sufficient command-reception capability to execute and if necessary change, major portions of a planetary encounter or orbital or lander operations sequence.

These various spacecraft capabilities have crystallized into two evolving design families defined by the types of missions required: the Pioneer spacecraft, which are spin-stabilized and dependent for most of their operational control on ground commands, and the Mariner spacecraft, which are actively stabilized in three axes and have a high degree of command and control capability on board the craft. There are advantages and disadvantages for each design and each stabilization mode. There are missions best suited to each design approach (Table 7).

Pioneers are well adapted to fields and particles measurement and low-resolution remote-sensing investigations for which the spinning of the spacecraft is an advantage and the lack of onboard command and control and of stable instrument orientation not an insurmountable handicap. The Pioneer Jupiter mission, and the adaptation of Pioneer spacecraft design to new requirements, has been described. Now this type of design is being adapted to a new kind of mission, described in the next section: carrying atmospheric probes to Venus.

The Mariner family of spacecraft has been in planetary exploration virtually from the start, as indicated earlier in Table 4. They have exhibited three facets of three-axis stabilization: sun orientation for thermal control and solar-energy acquisition from planar photovoltaic panels; Earth orientation, derived from spacecraft structure or achieved through controllable articulated mechanisms for high-gain, high-data rate communications; and planet orientation of an accurately controllable instrument platform for scanning, high-resolution remote-sensing investigations such as imaging and infrared and ultraviolet spectroscopy. Interest in the capability for high spatial and spectral resolution in these investigations has led to the development of a considerable onboard sequencing, data-acquisition, and data-processing capability, permitting observations which are integrated accurately in space and time. The Jupiter/Saturn Mariner, like the Jupiter Pioneer, is the first of its family to abandon solar power, but the Sun is retained as a primary celestial reference,

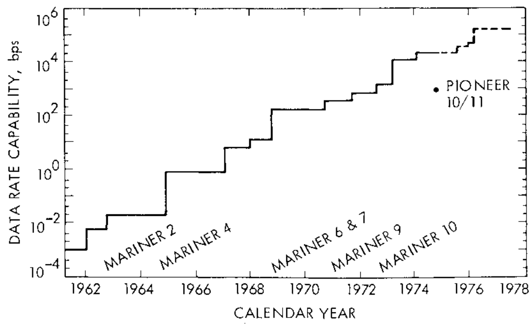

Fig. 24 Improvement in planetary data rate capability (normalized to 800,000 km range), 1964-74, with future performance projections.

and orientation requirements for the communications antenna and for planet and satellite remote sensing, and the requirements for integrated science sequences, are more stringent than on any previous mission. Again, the conduct of a planetary exploration flight is of little value without the capability to sense and observe, to acquire the desired measurements. One measure of our current capability in this field is a catalog of proven and applicable planetary flight instruments. Such a catalog is represented in part at least by the science payloads of the most recent U.S. spacecraft used in missions to Mercury, Mars, and Jupiter, given in Table 8.

A different and more useful measure of our state-of-the-art of planetary flight scientific instrumentation is represented in terms of functional application to future missions. We have experienced throughout the Mariner and Pioneer missions so far the transfer and adaptation of flight instruments and technique from one mission target to another, parallel to the evolution of new instruments. Earth-oriented and lunar instruments have been adapted to planetary targets, as well as adaptation from planet to planet. A distinction must be made between inner- and outer-planet applications of some instruments which depend on local solar-energy levels, such as visual or IR devices. Direct sensors of fields and particles, in-

Table 7 Characteristics of Pioneer and Mariner spacecraft

Characteristic	Pioneer 6-9	Pioneer 10-11	Mariner 1-5	Mariner 6/7	Mariner 9	Mariner 10
Mass, kg	48	228	200-260 kg	384	435	630
Payload, kg	18	33	15-27	59	70	70
Experiment types	Fields & particles	F&P and planetary	Planetary (scan) and F&P	Planetary (scan)	Planetary (scan)	Planetary (scan) and F&P
Spacecraft power (watts)	Solar (89)	RTG (140)	Solar (150-200)	Solar (380)	Solar (450)	Solar (505)
Stabilization	Spin	Spin	Three-axis	Three-axis	Three-axis	Three-axis
Telemetry rate, bps	8-512	248	8-33	270/16K	16K	22K/118K
Thrust maneuver capability	None	Multiple	One-two	Two	Many, plus orbit insertion	Many
Mission	Interplanetary	Jupiter flyby	Planetary flyby	Mars flyby	Mars orbit	Venus/ Mercury

Table 8 Scientific instrument complements for recent planetary missions

Pioneer 10/11	Mariner 9	Mariner 10
Magnetometers	Television cameras	Television cameras
Charged-particle detector	IR Interferometer-spectrometer	Plasma detectors
Geiger-tube telescope	Infrared radiometer	Infrared radiometer
Cosmic-ray telescope	Ultraviolet spectrometer	Magnetometers
Trapped radiation detector	S-Band radio science	Charged-particle telescopes
Ultraviolet photometer		Ultraviolet spectrometers
Imaging photopolarimeter		S/X-Band radio science
Infrared radiometer		
Asteroid-meteoroid detector		
Meteoroid detector		
S-Band radio science		

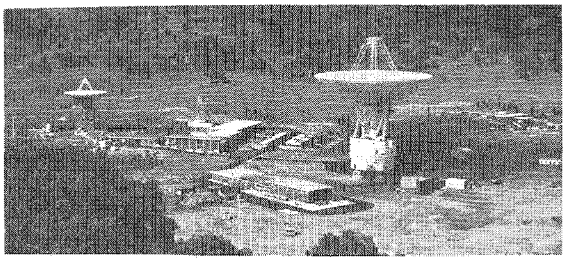

Fig. 25 Australian conjoint Deep Space Station, with 64 m antenna (right) and 26 m antenna (left), is one of three major stations of the Deep Space Network.

cluding gamma-ray detectors and magnetometers, for example, and self-illuminating devices such as radar are not affected by the waning of sunlight as one recedes from the inner planets.

In both existing and developing equipment, a broad instrumental capability exists, and the choice for planetary exploration science, like the choice of equipment to support all aspects of planetary exploration, is not so much what experiments to conceive and invent, but what to select and adapt, on the basis of integrated mission objectives.

C. The Earth Base

Even those of us involved in the planning and execution of planetary exploration tend sometimes to take for granted and ignore a major functional part of the exploration system, namely the base. This includes the Earth terminal net of the tracking and telecommunications system with its communications and control elements, the computation and data-processing facilities, and the mission operations function. These elements are not only essential for the receipt of planetary data, but for the operational and sometimes even the survival of the spacecraft. Without its base, the spacecraft is a projectile. With the base as the analog of a brain and the spacecraft of sense organs, the exploration system becomes a functioning organism.

The outermost element of the base is the net of tracking and communications stations which keep in touch with the spacecraft (up to continuous in extent). United States planetary missions use the Deep Space Network, a multi-mission facility which has evolved through the history of the space program. Stations are located in California's Mojave Desert, in Australia not far from Canberra, and near Madrid in Spain. Each station has a 64 m reflector antenna and one or more 26 m antennas (Fig. 25). These are diplexed to permit transmitting and receiving simultaneously; they are configured to operate at S-band, and an X-band capability is being added into the network. The first 64 m station supported the Mariner 5 mission in 1967; the full network of advanced antennas supported Mariner 10 last year. Continuous improvements in equipment have supported the growth in telemetry rates and tracking accuracy discussed earlier.

Mission control and computing facilities for planetary exploration are located at the Jet Propulsion Laboratory in Pasadena, where Deep Space Net control elements are also situated. Mission control and some data-processing facilities for Pioneer projects also exist at NASA Ames Research Center, receiving a direct telemetry feed from JPL.

The Doppler and ranging data are processed into trajectory information, becoming inputs to the navigation function, together with spacecraft-sensor data as appropriate. Navigation outputs take the form of position-vs-time estimates for the planetary encounter and maneuver requirements, which result ultimately in maneuver commands and programing sent up to the spacecraft. Engineering telemetry is processed and provided to spacecraft operators who keep track of the health of the flight equipment, sometimes originating commands or programing to change the spacecraft status. Scientific data are processed for quick presentation to experimenters and for the master data records used for subsequent analysis and interpretation. All these functions, including the processing of image data, are automated as much as possible in the interest of quick response when it is required, on the one hand, and flexibility on the other hand. Command processing—the handling of data sent to the spacecraft—has evolved similarly, with the driving imperatives being reliability and flexibility. As we contemplate future outer-planet missions, with relatively long operational periods and inevitably rising communications turnaround times, and more sophisticated inner-planet investigations, the need for maximum ground reliability and flexibility only increases further.

The integrating element, and the most complex, in the Earth base for planetary exploration is what we have come to call the Mission Operations System. It consists essentially of programs, procedures, and people. Unlike the telecommunications stations and computers, the elements of this system are oriented to a particular mission and are conditioned by its special requirements. The people naturally include operators whose experience has included a number of previous missions, but unlike Deep Space Station and computer operators their priorities are those of their mission. The operations team also includes the managers who have brought the mission to the flight phase, and the scientists responsible for planetary and other experiments. The scientists may interact to varying degrees in the conduct of flight operations, depending on the nature of the mission; only rarely are they passive receivers of data. On the Mariner 9 and 10 missions we have seen significant added value from active participation by experimenters in recommending particular operational activities, sometimes in real time. In summary, then, we see that the art of planetary exploration, as it has evolved over the past decade, is based on the development of many technologies, of diverse characteristics, and their integration on a continuing basis to support a series of missions.

D. Management Technology

Closely related to the Earth-based element of planetary exploration is the set of management attitudes and associated techniques. The development of a planetary exploration capability was paced almost as much by management state-of-the-art as by component/design/instrument limitations. In addition to usual management problems associated with any R&D undertaking, there are particular aspects of planetary exploration requiring special management considerations.

One obvious constraint imposed by planetary missions is that the launch schedule must be met. Planet positions with respect to earth restrict launches to periodic intervals varying from 4 months for Mercury to 26 months for Mars. Two planet missions such as the 1973 Venus/Mercury opportunity and the 1977 Jupiter/Saturn opportunity occur less frequently, at intervals on the order of a decade or more. Obviously, all of the activities of development, design, testing, integration and operations support, sometimes involving years of planning and implementation, must culminate with an inflexible end date. A normal mission development and preparation cycle varies from 3 to 4 years depending upon the mission scope and the starting point, i.e., the degree to which the mission objectives relate to previous experience and technology. During this time, a project organization must deal with a broad spectrum of activities from mission definition and design to hardware fabrication including electronic parts through system testing and launch support. For early planetary exploration efforts, Mars and Venus, the post-launch phase of the project was a relatively short period, and organizationally could be handled as an add-on. With orbiter missions to the inner planets, and the long flight times to the outer planets, the post-launch project phase consists of 2-4 years. Obviously the size and scope of the project organization during this period is significantly different. Yet, if a problem develops, personnel involved in an earlier stage of the project must be available for problem solving.

The project management problem for planetary missions is therefore one of maintaining the proper mix of people throughout a project where the scope of activity changes drastically. People starting on a planetary exploration project must wait as long as 6-8 years for the realization of the mission objectives.

The definition of a planetary mission often involves planning a series of science investigations for a planet about which little is known. Because the mission is exploratory, and the investigation possibilities are limitless, the guidelines for deciding on the priorities of the investigations are quite arbitrary. Yet the investigation objectives directly influence the design approach and resources required for the spacecraft and operational elements of the mission. A balance must be struck between the investigator's desire for continual study, iteration and infinite flexibility and the implementers tendency to select something he knows he can do and see what can be accomplished with it. The balance between these two issues has, justifiably, varied with the maturing of a planetary exploration capability. Initially, a major mission objective was to "get there," and investigation objectives had to be consistent with maximizing that objective. At the current stage of planetary exploration, the scope of a mission is determined primarily by the investigation objectives selected and the resources allocated. A major aspect of current project organizations is the involvement of the science community from initial concept definition through all subsequent stages of mission planning and implementation. Clearly, not all science desires can be implemented on a given mission, but involvement in the tradeoffs leads to an understanding of mission requirements and constraints. The proper blending of the diverse and often conflicting requirements into a viable project organization that achieves the exploration objectives is an art, not a science. It is an art that has been developed at great expense of time and money. It exists at a high degree of competence and timeliness to take advantage of the many exploration opportunities that are within our grasp.

V. The Coming Opportunity

At this moment in the history of planetary exploration we stand poised between ability and opportunity. In a way this is the case throughout a period of growth and progress, but the present time stands out above the surrounding era of the exploration of the solar system for reasons rooted in the past and in the future. The reasons of the past—the high development of planetary exploration technologies and their demonstration in recent achievements—have been apparent in preceding sections. The reasons of the future—the recently perceived opportunities for special planetary investigations and flight missions of the next decade—are to be described in this section. Many of these have emerged from planning studies associated with the Outer Planet Grand Tour proposal and with Mars landing and surface investigation proposals; others occurred during studies of the application of various investigation programs to planetary targets. The planetary projects already authorized and underway in NASA cover a broad spectrum of inner- and outer-planet investigations. Let us now examine these three efforts.

A. Authorized Near-Term U.S. Planetary Projects

Over the next three and a half years the United States plans to launch missions to land on Mars, fly by and observe the Jupiter and Saturn systems in detail, and probe the atmosphere of Venus. The first of these is the Viking Mars 1975 mission.[21] Its two composite spacecraft are to be launched this summer, using Titan/Centaur launch vehicles. Almost a year later each will arrive at Mars, where the spacecraft propulsion system will place the 1250-kg Lander capsule and 2350-kg Orbiter spacecraft in a synchronous elliptical orbit. Following a surface survey to validate previously selected landing sites, the Orbiter will release the landing capsule. The Lander spacecraft will have been an inert passenger sealed up like a chick embryo in its biological eggshell up to this point.

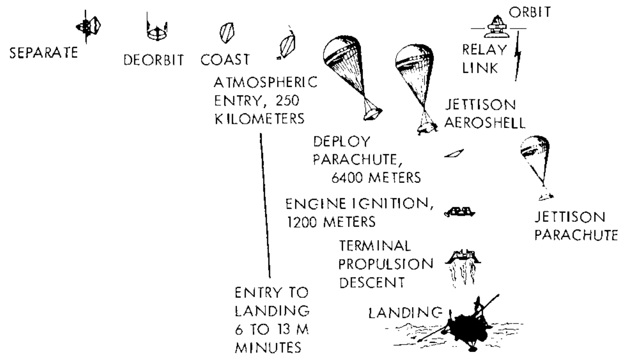

Fig. 26 Viking landing sequence.

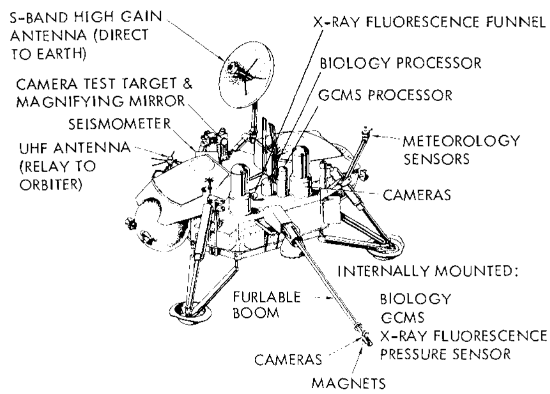

Fig. 27 Viking lander configuration.

Table 9 Viking scientific experiments

Mission phase	Experiments	Principal scientists
Orbiter	Television imaging	M. H. Carr, U. S. Geologic Survey
	IR Thermal mapping (surface)	H. H. Kieffer, UCLA
	Water vapor mapping (IR)	C. B. Farmer, JPL
	S/X-Band radio	W. H. Michael, NASA Langley
Aeroshell entry	Ion and electron retarding potential analyses	
	Natural gas mass spectrometry Upper atmospheric pressure and temperature measurements	A. O. C. Nier, U. of Minn.
Lander	Imaging	T. A. Mutch, Brown U.
	Biology detection	H. P. Klein, NASA Ames
	Molecular mass spectrometry, gas chromatography, and x-ray spectrometry	K. Biemann, MIT
	Meteorology: variations in pressure, temperature, and wind velocity	S. L. Hess, Florida State U.
	Seismometry (3 axes)	D. L. Anderson, Caltech
	Surface magnetic and physical properties	R. B. Hargraves, Princeton U. R. W. Shorthill, U. of Utah

After coasting out of orbit, the landing system enters the upper atmosphere, employing high-speed aerodynamic braking, parachutes, radar-controlled rockets, and legs with shock absorbers to bring the remote laboratory to rest on the surface of Mars (Fig. 26).

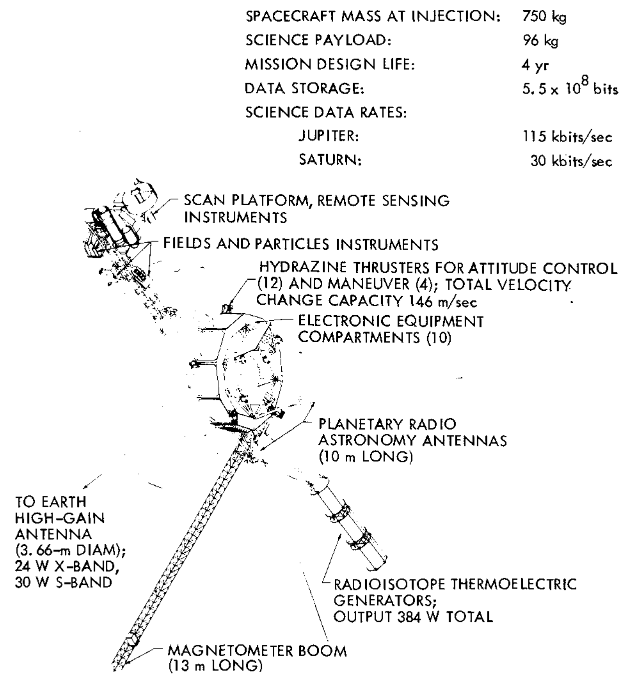

Fig. 28 Configuration and characteristics of Mariner Jupiter/Saturn spacecraft.

Table 10 Mariner Jupiter/Saturn scientific experiments

Experiment	Principal investigators
Television imaging	B. Smith, U. of Arizona
Infrared interferometric spectrometry	R. Hanel, Goddard Space Flight Center
Plasma wave	F. Scarf, TRW
Ultraviolet spectroscopy	A. L. Broadfoot, Kitt Peak National Observatory
Photopolarimetry	C. Lillie, U. of Colorado
Solar plasma	H. Bridge, MIT
Low-energy charged particles	S. M. Krimigis, Johns Hopkins University, Applied Physics Laboratory
Cosmic rays	R. E. Vogt, Caltech
Magnetic fields	N. F. Ness, Goddard Space Flight Center
Planetary radio emissions	J. Warwick, U. of Colorado
S/X-Band radio science	V. R. Eshleman, Stanford U.

The Viking Orbiter resembles an enlarged Mariner Mars 1972 spacecraft, and its remote-sensing role is similar to that of Mariner 9, with a somewhat narrower focus. While the Landers are operating, the Orbiters serve as communications relay stations, interchangeably. (The Landers can also communicate directly at lower rates.) It is planned that upon completion of Lander-supporting functions, one Orbiter or the other would extend its observations to a wider scope, permitting study of secular changes since the Mariner 9 survey.

The Viking Lander (Fig. 27), a new design related slightly to the Surveyor unmanned lunar-landing craft, is equipped to obtain images of its landing site, to obtain physical, meteorological, and seismic information, and to pick up and

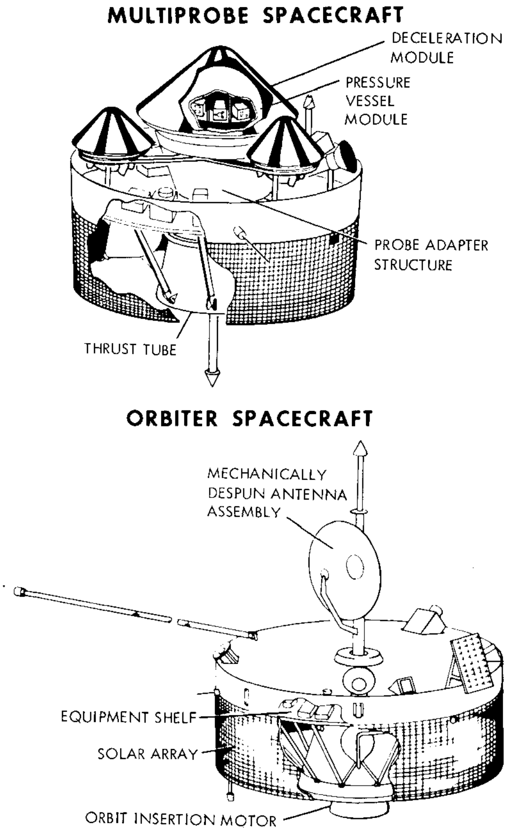

Fig. 29 Pioneer Venus 1978 spacecraft configuration.

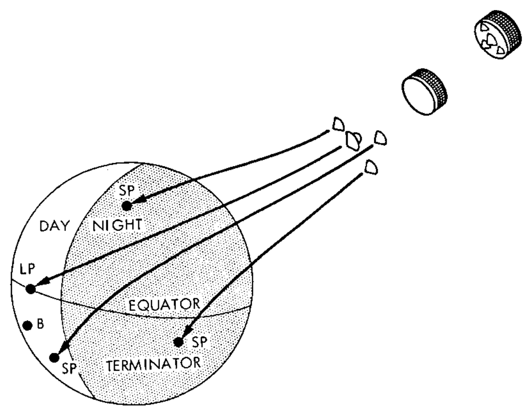

Fig. 30 Pioneer Venus 1978 probe targeting.

process samples of the surface of Mars. These samples will be subjected to chemical analysis and biological tests. The key objective of this undertaking is the search for evidence of life on Mars, past, present, or future. Scientific payloads of the Viking Orbiter and Lander are listed in Table 9.

Mariner Jupiter/Saturn 1977 is the next scheduled flight mission in the U.S. planetary exploration program.[22] This project will launch two outer planet spacecraft in 1977, using Titan/Centaur vehicles with an additional Propulsion Module on each spacecraft, toward 1979 encounters with Jupiter and 1981 encounters with Saturn. Measurements will be made of the interplanetary medium between planets, and each spacecraft will spend many weeks observing the Jovian and Saturnian systems. The 750-kg outer planet Mariner (Fig. 28) is designed to support eleven major scientific experiments, with five instruments on a fully-articulated scan platform, and to return the data they acquire to Earth at high rates (115 kbits/sec from Jupiter, 30 kbits/sec from Saturn). These capabilities, together with the sophisticated navigation and control capabilities and the high resolution and sensitivity of the remote sensing instrumentation, assure that not only

Table 11 Pioneer Venus scientific experiments

Mission element	Experiment	Principal scientists
Large probe	Neutral mass spectrometer	J. Hoffman U. of Texas, Dallas
	Gas chromatograph	V. Oyama, NASA Ames
	Atmospher structure	A. Seiff, NASA Ames
	Solar radiometer	M. Tomasko, U. of Arizona
	Infrared radiometer	R. Boese, NASA Ames
	Cloud particle size spectrometer	R. Knollenberg, Particle Measurement Systems
	Nephelometer	B. Ragent, NASA Ames
Small probe	Atmosphere structure	A. Seiff, NASA Ames
	Nephelometer	B. Ragent, NASA Ames
	Net Flux radiometer	V. Suomi, U. of Wisconsin
Spacecraft bus	Neutral mass spectrometer	U. Van Zahn, U. of Bonn
	Ion mass spectrometer	H. Taylor, Goddard Space Flight Center
Earth-based radio experiments	DVLBI	G. Pettengill, MIT
	Tracking, turbulence	R. Woo, JPL
	Tracking, propagation	R. Croft, Stanford U.
	Tracking, winds	A. Kliore, JPL

Jupiter and Saturn (and the Rings) but at least one or two satellites of each planet may be examined in fine detail. Perhaps half-a-dozen more satellites can be characterized geologically, and observed at moderate range. The scientific investigations of this mission are listed in Table. 10.

The last of the three planetary explorations now on NASA's calendar is a return to Venus in 1978. This Pioneer mission plans the entry of multiple probes into the atmosphere of Venus, with a companion vehicle to the probe carrier injected into an orbit of Venus. Each Pioneer Venus spacecraft is to be launched by an Atlas/Centaur vehicle. The spin-stabilized probe carrier, with one large probe and three small ones, has a mass of about 816 kg. The spacecraft configurations are shown in Fig. 29. The probes will be released about 20 days before encounter; the carrier spacecraft will then decelerate so that it enters the atmosphere last. The probes and spacecraft will be targeted to permit correlation of their results, with comparison of atmospheric data over a wide region (Fig. 30). About 18 kg of scientific instruments will be carried aboard the spacecraft bus, plus 32 kg on each small probe. The instruments are listed in Table 11, together with the Earth-based ratio experiments.

B. Opportuntities of the Next Decade

The first factor defining opportunities for planetary exploration is the geometry of the solar system. To the Earth-based planetary explorer, it is expressed in planetary apparitions; to the flight-project planner, it takes the form of launch opportunities, offset from the schedule of apparitions but showing the same periodicity, except in the case of multi-

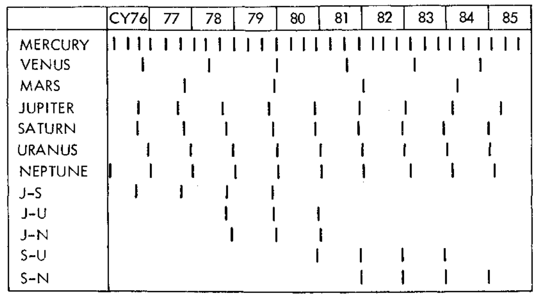

Fig. 31 Planetary launch opportunities for the next decade, including Jupiter- and Saturn-based dual outer-planet opportunities. All feasible launch opportunities are shown, regardless of arrival or intermediate-flyby conditions.

planet, gravity-assisted missions, which show a beating frequency between the individual planets. Planetary launch opportunities for the next decade are shown in Fig. 31.

Strategic considerations for exploiting these opportunities have been discussed in many NASA reviews, by an AIAA Review,[19] and, with respect to particular areas such as Mars exploration or the Outer Planets, by various scientific panels.[24,25] A different and more important strategic consideration is taken up by the International Decade proposal discussed in the next section. I believe a planetary-exploration strategy compatible with essentially all such positions is implicit in the existing NASA projects, which are addressed to a variety of planets. This pluralistic approach, of finding out as much as possible on a broad front, and letting technical achievements and advances flow from one mission area to another, has proved viable in the past.

Previous and ongoing efforts to explore Venus have dealt with questions of the plasma interaction above the planet and of atmospheric dynamics. Only Earth-based radar astronomy has started mapping the solid surface beneath the cloudy atmosphere. We may hope that at least partial understanding of the behavior and composition of the atmosphere, including some data on micro dynamics and minor constituents, will be available after the 1978-79 mission opportunity. However, relatively high-resolution mapping of surface features is an essential key to understanding the solid-body planetology and, if present, tectonics. This calls for a large, sophisticated spacecraft equipped with a powerful, sensitive radar and placed in a high-inclination or polar orbit. Synthetic-aperture radars adaptable to such an application have been developed; one such was employed on the Apollo 17 orbiting Command Module.

Mariner 10 has raised at least two major areas of interest in the planet Mercury. The first is the nature of the planet's magnetosphere, the character of the planetary magnetic field, and the dynamics of the solar-plasma interaction. The second is the body problem, the enigma of what was believed to have to be a homogeneous body with a high bulk density and an apparently low-density surface. Both of these puzzles cry out for a long-life orbiting observer, many of whose experiments would likely be in the direct-sensing fields and particles area, together with TV mapping and measurement of the gravitational field. Such an observer could likely, and perhaps necessarily, make a number of measurements of solar emissions as well.

Future exploration of the chemistry, meteorology, and hoped-for biology of Mars must clearly be determined and conditioned by the results of the Viking 1975 mission. In advance of those results, we can examine two aspects of desirable future Mars investigations: the shape of post-Viking surface missions, and certain areas outside the main thrust of Viking landing objectives. Regardless of the results of in-situ remote investigation of a few preselected sites on the Martian surface, there are two directions in which this kind of exploration must be extrapolated: breadth and depth of analysis. The first implies a Mars surface rover, the second the return of Martian samples for analysis on Earth. Options for the latter mission have been described recently.[26] Either of these undertakings would be difficult, complex, and expensive, the sample return considerably more so. However, studies have shown that they are within reach of current technology, and the prospect of acquiring a documented sample of the planet Mars—especially given a sensible probability that it might contain evidence of extraterrestrial life—places a considerable value on this option.

Leaving aside the biological and chemical questions, the study of global Martin dynamics, both subsurface and atmospheric, holds promise for our understanding of the origin and history of our type of planet, in conjunction with similar studies of Mercury, Venus and the Earth. Note that comparative studies of the inner planets, climaxing in Mariner 10 data from Mercury, made possible the recent challenges to the conventional view of inner-planet cosmogony. Thus a long-life polar orbiter above Mars, capable of sensing variations in body structure as well as atmospheric and surface changes, might find a valuable role in comparative planetology.

The outer planets of the solar system harbor so many large questions at present—beginning, practically, with "what are they?"—that they could probably absorb a whole space program for a century, given the known tendency for early explorations to raise more questions than they settle. The systems of Jupiter and Saturn are so grand and varied that the established Pioneer and Mariner missions will at best organize the questions and set the basis for further research. Though we tend to group the outer planets according to their similiarities—and their categorical differences from the terrestrial planets—we shall soon have to come to grips with the significance of their differences. Mariner Jupiter/Saturn 1977 is intended to begin this comparative study, but this mission is likely to be all but overwhelmed by rich, new data on each individual planet and satellite observed. In addition, by comparison with Jupiter, we know next to nothing about the next two planets, Uranus and Neptune; but what we know suggests differences from Jupiter and Saturn rather than smaller-scale copies. Pluto is an enigma, and one which, in my opinion, can reasonably be left out of the next decade.

The atmospheres of the giant planets are visible while their surfaces are not; the next step after remote sensing of these deep oceans of gas is direct observation through entry probes like those being designed for Venus. Atmospheric probe missions to Jupiter, and via Jupiter swingby to Saturn, have been studied and found technically feasible for the next decade. A similar probe mission combined with a Uranus flyby (via Jupiter swingby) has been studied as well; the 1979 launch opportunity provides for a unique polar approach because of the inclination of the pole and satellite plane of Uranus. A Jupiter/Uranus opportunity will not recur until the 1990's.

Another essential step in the exploration of the outer planets is the detailed, long-period survey of the individual planet and its surroundings, by an orbiting observer. Jupiter is the logical first candidate for such an investigation, both because of its relative proximity and because of the breadth and intensity of interest in its unique properties and phenomena.Both a polar and an equatorial orbiter would be desirable in the case of this planet, and gravity-assisted orbit changes using satellite gravitational fields would permit considerable excursions—for example probing the wake and the bow shock, as well as many satellite encounters —economically. A Jupiter orbiter mission for the 1980-81 launch opportunity has been studied recently.[27] A final point should be made about the opportunities to explore the outer planets. While launch opportunities for direct flights to Jupiter and the further bodies come annually, Jupiter-swingby opportunities are much less frequent. The energy required to reach even Jupiter is considerable (though it is lower than average in 1980-81), and Jupiter swingby, as we have seen in Fig. 22, is by far the most economical to reach the other outer planets. Even at best, outer planet flights are demanding of launch energy, mission reliability, funds, and operating time. There will not be very many such missions—and never enough. Therefore we must get the greatest possible value from them, in terms of significant and valid new scientific information. To this end, NASA has requested careful planning studies, both of mission feasibility and of scientific objectives, and has enlisted the aid of a number of scientific advisory groups and committees to look into the implications of such missions. The work thus far of these scientists reveals great scientific potential in outer-planet exploration.

C. An International Program Proposal

To obtain the full value of these planetary exploration prospects, an integrating and unifying mechanism is required; something like the International Geophysical Year. Just such an institutional framework has been formally proposed by W. H. Pickering: The International Solar System Decade, presented to COSPAR last year. The concept is for an international, interdisciplinary effort to explore the solar system. It begins with the Viking mission and could close a decade later with a Mars sample-return mission. However it goes much further than just a proposed series of flight missions. Like the IGY, it envisions cooperative earth-based observations as well, full sharing of data, and an active collaboration in spacecraft-based investigations. The Mars sample return mission, with its multiple flight vehicles, and broad needs for technical and scientific support activities, could provide many opportunities for international collaboration at the project level.

VI. Conclusions

Planetary exploration as I see it and have described it in this lecture is a thriving and effective scientific and technical enterprise. It is based solidly on a broad field of planetary data and discoveries, mature technologies, and highly capable institutions. We are presently examining a wide range of important opportunities for further major work in the coming decade.

In recent years we have mapped the silent, towering volcanos, the empty canyons, and the battered old plains of Mars. We have charted the spinning clouds and begun to probe to the hellish surface of Venus. We have opened new gates of exploration and theory with exciting discoveries at Mercury and at Jupiter. With all of these researches, we have begun a vast new study of the history, nature, and dentiny of our own planet, the Earth. The interplanetary geometric opportunities, the advanced state-of-the-art, and the growing base of scientific knowledge assure that the coming years of planetary exploration can be richly rewarding. Yet at the same time, the major investment in this enterprise has already been made, and recent missions, led by Mariner Venus/Mercury 1973, have demonstrated that we can pursue these high goals at relatively low cost, acquiring a wealth of new knowledge at a modest expenditure. Yet it is clear that however cost-effective a program is, it still incurs costs; however economically sound this enterprise, it still requires economic support. In the case of planetary exploration, this means public support. Thus a new perspective is called for: the outside view. What does planetary exploration offer to the outside public?

First, it offers, and has offered, a new horizon for achievement and for challenging the unknown, at the global, national, institutional, and individual levels. As A. C. Clarke has put the point, "Men need the mystery and romance of new horizons almost as badly as they need food and shelter."[28] Planetary exploration will soon offer, as well, a large new advance on the question of whether our planet's creatures are or have been alone as living species in the solar system.

Second, it has offered, since its inception, a medium for international competition and collaboration in science and advanced technology. Soviet-American competition in space, and their limited but growing exchanges, have constituted the leading edge of the process of global detente. Planetary exploration, as it happens, was the area in which the United States first pulled ahead in the "space race," and the area in which the first real-time space data exchange "hot line" was established.

Third, it has stimulated advances along a broad front of research and technology, in a way which used to be reserved to war. However this growth is based purely on domestic expenditure, and excludes destruction and disaster. Planetary exploration is at the very frontier of the space program, technically as well as physically, but the technical improvements it stimulates are no less applicable to easier jobs by having been developed to solve nearly impossible problems.

Fourth, it stimulates education and the popularization of science at all levels. While planetary exploration is bringing home the information to support new studies of planetary accretion, magnetism, atmospheric dynamics, and solar interaction, the whole process takes place publicly. The pictures of Mars, Venus, Mercury, and Jupiter which are data to the scientist are news to the public. All Americans, and a large proportion of humanity, have vicariously walked upon the moon and looked down upon Earth's weather; they have also ranged many hundreds of millions of miles out into the solar system, and sat beside scientists to see Mercury's craters or Jupiter's south pole for the first time.

How can we better involve and integrate the people—especially Americans, but essentially all the ultimate beneficiaries of the new knowledge and other values of planetary exploration? The planetary program itself has shown the degree to which representatives of many scientific and technical disciplines have joined together in this enterprise. The International Geophysical Year, in which space exploration was born, showed how nations could join in a global scientific effort. The proposed International Solar System Decade would provide just this mechanism for the future. Though its avowed purpose is to provide an interdisciplinary and international scientific medium, like that of the IGY but extending farther in time and space, it would inevitably have a considerable educational and popular impact as well.

In conclusion, therefore, I see planetary exploration as an important if modest scientific and technical enterprise of the present and recent past, with strong opportunities in the near future to continue the solid work now underway. But I believe that the value which will be placed on this effort by future generations will be immense. Our technical struggles, scientific arguments, and modest flight projects will become the base for greater adventures, new science and technology, and newer and wider horizons. Let's be sure that those future generations can't say that we stood on the threshold of unraveling the secrets of mankind's existence and then turned our backs.

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